PATHFINDER

CRYOGENIC FLUID DEPOT PROGRAM PLAN

Winter 1988-1989

Office of Aeronautics and
Space Technology

National Aeronautics and
Space Administration
Washington, D.C. 20546

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daw (9-29-88)

FOREWORD

Project Pathfinder is an important technology initiative which will allow the National Aeronautics and Space Administration (NASA) to develop critical capabilities to enable future space missions. Pathfinder does not, in itself, represent a commitment to any particular mission. Nevertheless, Project Pathfinder will make future national decisions regarding human exploration of the Solar System possible. Through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that will support a wide range of potential future NASA missions.

The Pathfinder Cryogenic Fluid Depot Program will develop and validate the technologies required to perform storage, supply, and transfer of subcritical cryogenic liquids in a low-gravity space environment. The long-term goal of this technology program is to enable fueling/cryogen resupply operations for future spacecraft and space transportation vehicles in a low-gravity environment. In the first phase, the program will be focused on cryogenic fluid management technologies--including liquid storage, liquid transfer and handling, liquid supply, structures and materials, advanced instrumentation, and a cryogenic fluid management flight experiment definition. Also, studies will be conducted to identify depot user requirements, define a baseline cryogenic fluid depot concept, identify technologies required to develop the defined depot concept and prepare technology roadmaps to illustrate the time phased development of all required depot technologies.

For additional information on the Cryogenic Fluid Depot Program, or this document, please call the OAST Propulsion, Power, and Energy Division (RP), at (202) 453-2847.

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1.0 EXECUTIVE SUMMARY

1.1 Technology Project Goals & Objectives

The goal of the Cryogenic Fluid Depot Project is to develop the technology data base required to perform storage, supply and transfer of subcritical cryogenic liquids in a low-gravity space environment. The long-term goal of this technology program is to enable fueling/resupply operations for future spacecraft and space transportation vehicles.

Project objectives include: (1) Identification of the technologies required to provide an adequate data base for the design of an cryogenic fuel depot, (2) Assessment of the present state of readiness of the identified technologies, (3) Determination of the readiness goal required to provide an adequate data base, (4) Performance of research and development activities necessary to meet the readiness goal for each technology, (5) Creation of a design data base for incorporating the technology development activities into a usable format for the design of cryogenic fuel depots.

1.2 Organization and Management

The organization chart and management personnel of the Cryogenic Fluid Depot Program is illustrated in figure 1-1. The overall program will be managed by a Program Manager resident at NASA Headquarters in the OAST Propulsion, Power and Energy Division (Code RP). The Program Manager will have the responsibility of coordinating with other programs and Pathfinder elements to avoid duplication of effort and to ensure that all technologies are being adequately addressed.

1.2 Organization and Management (continued)

NASA LeRC has been designated as the Lead Center for the Cryogenic Fluid Depot program and will be responsible for the Technology Project Management. The Technology Project Manager will have the responsibility within the program of insuring that specific technology efforts are coordinated through matrixed responsibilities in each technology discipline.

Included under the direction of the Technology Project Manager, is a large portion of the staff of the LeRC Cryogenic Fluid Technology Office (6200), several members from the LeRC Advanced Space Analysis Office (6800), and support individuals designated by Johnson Space Center (JSC) and the Jet Propulsion Laboratory (JPL). The Marshall Space Flight Center (MSFC) will serve in a support and advisory role to the Technology Project Manager. A description of the MSFC role is contained in a Memorandum of Understanding (MOU) prepared by NASA Headquarter Codes R and M (Appendix A). Following completion of the system integration studies, additional NASA centers may be involved.

1.3 Schedule & Deliverables

Figure 1-2 provides a schedule for the first five years of the project (FY 1989-1993). Table 1-1 provides a milestone table with accomplishments and deliverables list for the first five years of the project (FY 1989-1993). Note that the numbers shown on the schedule in figure 1-2 correspond to the milestones indicated in table 1-1. Furthermore, the schedule and milestones associated with elements other than system integration (task 1.1) and cryogenic fluid management (task 1.2) are yet to be determined.

1.4 Resources

Resources for the first five years of the program are summarized in table 1-2. The funding shown is adequate for the system integration (task 1.1) and the cryogenic fluid management (task 1.2), exclusive of flight experiments. It is likely funding will need to be increased for the development of technologies in the other tasks (1.3 through 1.6).

2.0 INTRODUCTION

2.1 Project Pathfinder Overview

Project Pathfinder is a National Aeronautics and Space Administration (NASA) initiative to develop critical technologies for the future of the U.S. civilian space program. Pathfinder does not, in itself, represent a commitment to any particular mission. However, through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that can be applied in a wide range of potential future NASA programmatic thrusts: (1) Exploration, (2) Operations, (3) Humans-In-Space, and (4) Transfer Vehicles.

The Cryogenic Fluid Depot Program is one of four programs under the Operations thrust. More information on Pathfinder can be found in the Pathfinder Program Plan.

2.2 Document Purpose & Scope

The goal of this document is to provide a detailed plan to accomplish the goals and objectives set forth in the Cryogenic Fluid Depot Program Plan. The purposes of this

2.2 Document Purpose & Scope (continued)

document are (1) to provide the traceability to mission-derived technology requirements, (2) to specify the work breakdown structure to the work package level, (3) to define the technical approach and description for each of the work packages, (4) to define the management approach assigning areas of technology development to the matrix organizational structure, (5) to establish funding and workforce requirements and associated schedules, milestones and deliverables, and (6) to provide for the necessary documentation to the successful accomplishment of constructing the Cryogenic Fluid Depot design data base.

3.0 CRYOGENIC FLUID DEPOT TECHNOLOGY PROJECT OVERVIEW

3.1 Mission Studies and Technology

On going NASA and Department of Defense (DoD) mission planning include spacecraft that will be launched into low Earth orbit (LEO) with limited or no cryogenic fluids on-board (for example, fuels-such as liquid hydrogen and liquid oxygen, or coolants-such as liquid nitrogen). Such launch scenarios may be preferred for a variety of reasons; these include launched mass reduction to conform with launch vehicle capabilities, thermal performance optimization, and risk reduction. Cryogenic fluids for these spacecraft will be transported to orbit separately, and then transferred to the user-spacecraft for operations. Periodic resupply of cryogens may also be required in order to extend the useful life of some spacecraft or payloads accommodated on the Space Station.

3.1 Mission Studies and Technology (continued)

In order to provide a "Cryogenic Fluid Depot" capability, techniques for the long-term storage of cryogens in LEO, and elsewhere, will be required. Transfer of cryogenic fluids from storage to user-spacecraft in a low-gravity environment will also be required. Also, a variety of supporting services technologies such as robotics for spacecraft manipulation during refueling may be required.

A variety of future U.S. space missions and operations will depend upon the availability of space-based cryogen supplies. The viability of a space-based Space Transfer Vehicle (STV), for example, will require on-orbit cryogen resupply. Also, nearer-term robotic Solar System exploration missions,such as the planned Mars Rover/Sample Return (MRSR) mission, could be substantially enhanced by the capability to "top-off" upper stages in LEO.

Piloted missions to Mars will (under currently feasible scenarios) be impossible without propellant supplies at an Cryogenic Fluid Depot. Piloted Mars mission scenarios currently under study will require on-orbit assembly of the piloted spacecraft from separately launched mission elements. The total mass in LEO of such a vehicle could exceed one million pounds, seventy-five percent (75%) of which would be propellants, with possible additional cryogens for life support and/or instrument cooling. In addition, this mission would require cryogen storage for over two years to fuel return-transit staging from Mars orbit.

3.2 Technology Assessment

Three systems for managing cryogenic fluids in a space environment currently exist. First, there are small-scale storage and supply systems for superfluid helium. Second, there are small-scale supercritical fluid supply systems for hydrogen and oxygen. Lastly, there are large-scale vehicle cryogen propulsion systems. None of these systems meet critical requirements for long-term storage, supply and transfer of liquid hydrogen and liquid oxygen or the requirements of vehicle, tankage, and facility operations in the low-gravity space environment.

Current technology programs are focused on developing a large-scale, space-based system to meet these requirements. Analytical models are under development, test facilities are being up-graded, and contracting efforts to perform in-space experiment are being planned.

3.3 Cryogenic Fluid Depot Program Goals and Objectives

The goal of the Cryogenic Fluid Depot Program is to develop the technology base required to perform storage, supply, and transfer of subcritical cryogenic liquids, in a low-gravity space environment. The long-term goal of this technology program is to enable fueling/resupply operations for future spacecraft and space transportation vehicles in a low-gravity space environment.

3.3.1 Program Objectives

A. Development of depot conceptual designs from which critical technology areas will be identified, since the criticality of a technology depends on the depot concept assumed.

B. Performance of critical research and advancement of technology readiness levels in the areas of fluid management and potentially in the areas of structures and materials, orbital operations and logistics, depot operations and safety. This will include large-scale ground system testing and/or analytical modeling of all critical technology items considered to be enabling to the operation of a depot.

C. Definition of in-space experiment requirements for flight testing, even though flight experiment development is not currently covered by this program.

3.4 Technical Approach

Studies will be performed to identify cryogenic fluid user requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology assessment analysis will be prepared which defines the criticality of the identified technology, assesses the current state of technology readiness and the state of technology readiness required for

3.4 Technical Approach (continued)

the development of an operational cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of the work in providing the technology readiness levels required. These assessments will be used to lay out a time-phased technology development program in each area.

The use of cryogenic fluid management technologies is inherent in all potential cryogenic fluid depot concepts. A detailed technology roadmap and program was developed under the R&T base program in FY88.

The program includes analytical modeling, ground-based experimentation and future flight experimentation definition. Flight experimentation requirements will be defined since they are required for technology development, even though such experiments are not in the scope of this project.

Cryogenic fluid management technologies have also been identified as the most critical area for development to enable a cryogenic fluid depot. On the basis of that assessment, the overall Pathfinder Cryogenic Fluid Depot Program emphasizes the development of these technologies in the near term. Once mission studies, user needs and requirements, and depot concepts are developed, it is conceivable that additional technologies may be developed. An initial assessment of some potential technologies which may be required was performed at a workshop held at LeRC in October 1987 (Reference 1). The results of that workshop were used to develop the approximate scope for the Cryogenic Fluid Depot program.

4.0 MANAGEMENT PLAN

4.1 Overview

The work breakdown structures for the six major tasks have been tentatively identified for the Cryogenic Fluid Depot Project. The tasks are; system integration (1.1), cryogenic fluid management (1.2), depot operations (1.3), structures and materials (1.4), orbital operations and logistics (1.5), and safety (1.6). Activities for tasks 1.1 and 1.2 are firm at this time and the work required for tasks 1.3 through 1.6 are tentative pending the results of the mission studies of task 1.1. A detailed description of the work breakdown structure can be found in section 4-2. The organizational elements and management personnel to implement tasks 1.1 and 1.2 of the Project Plan are shown in figure 1-1 and are described in section 4-3. Reporting requirements and responsibilities are detailed in section 4-6. Copies of the Pathfinder Program Plan and the Cryogenic Fluid Depot Program Plan can be obtained at NASA Headquarters. Identified in section 4-7 are the top-level advisory committees established to provide direction to both the management and the technical objectives of the Cryogenic Fluid Depot Project. Finally, the coordination of the Program with complementary and mission study programs within all of the major NASA Headquarters Offices are described in section 4-4.

4.2 Work Breakdown Structure

The Cryogenic Fluid Depot Project is tentatively divided into six major tasks: (1) System Integration, (2) Cryogenic Fluid Management, (3) Depot Operations, (4) Structures and Materials, (5) Orbital Operations and Logistics, and (6) Safety. Figure 4-1 illustrates the project work breakdown

4.2 Work Breakdown Structure (continued)

structure. A task and subtask work breakdown structure are provided for the two firm tasks, the system integration (1.1) shown on figure 4-2 and the cryogenic fluid management (1.2) shown on figure 4-3. The cryogenic fluid management task (1.2) has been further described in a subtask and a work package work breakdown structure presented in figures 4-3a through 4-3f. The remaining task and subtask work breakdown structures for depot operations (1.3) structures and materials (1.4), orbital operations and logistics (1.5) and safety (1.6) are TBD's depending on the completion of task 1.1 and figures 4-4, 4-5, 4-6, and 4-7 are supplied to accomodate potential future activities.

4.3 Organization and Management Structure

The organization chart and management personnel of the Cryogenic Fluid Depot Program is illustrated in figure 1-1. The overall program will be managed by a Program Manager resident at NASA Headquarters in the OAST Propulsion, Power and Energy Division (Code RP). The Program Manager will have the responsibility of coordinating with other programs and Pathfinder elements to avoid duplication of effort and to ensure that all technologies are being adequately addressed. NASA LeRC has been designated as the Lead Center for the Cryogenic Fluid Depot program and will provide responsibility for the Technology Project Management. The Technology Project Manager will have the responsibility within the program of insuring that specific technology efforts are coordinated through matrixed responsibilities in each technology discipline. Included is a large portion of the staff of the LeRC Cryogenic Fluids Technology Office (6200), several members from the LeRC Advanced Space Analysis

4.3 Organization and Management Structure (continued)

Office (6800), and support individuals designated by Johnson Space Center (JSC) and the Jet Propulsion Laboratory (JPL). The Marshall Space Flight Center (MSFC) will serve in a support and advisory role to the Technology Project Manager. A description of the MSFC role is containedin a Memorandum of Understanding (MOU) prepared by NASA Headquarters Code R and M. (Appendix A)

LeRC will have responsibility for leading the development of Technology Project Plan and for administration of the Plan through the program. All participating centers will be responsible to the project manager for all matters pertaining to their assigned tasks including resources, program responsibilities, and administrative matters pertaining to reporting, schedule and milestones.

4.4 Program Coordination

The Cryogenic Fluid Depot Program element of Pathfinder will be closely coordinated by the Program Manager within Code RP with appropriate personnel in the Office of Space Flight (OSF). Within OAST, coordination will also be maintained by Code RP with the on-going CSTI programs in the area of automation and robotics in OAST/RC, with OAST/RM in the area of materials and structures and OAST/RX in the area of flight experimentation. In addition to mission analyses and requirements definition within the program, this effort will also be coordinated with the missions studies activities of the Office of Exploration (OEXP), the Office of Space Science and Application (OSSA), the Office for Space Operations (OSO), and the Office of Space Station (OSS). As appropriate, mission enhancements through technology applications will be recommended to those offices. A systematic

4.4 Program Coordination (continued)

approach to the technology issues of a space-based fluids depot will begin with the definition of the system requirements. These requirements are generated by the mission which a depot will support. These requirements will be collected from the user organizations (Codes C, E, M, S, and Z) and catalogued in a data base. Depot conceptual designs that satisfy these requirements will be generated from which critical technology areas can be identified.

Conceptual designs of space depots will be generated that support the user's requirements. This portion of the studies will require close coordination with efforts at LaRC (Code Z sponsored) which are creating conceptual designs from the perspective of mission planners. If these designs are at a level sufficient to identify technology issues, they should be incorporated in these studies.

Since the criticality of a technology depends on the depot concept assumed, these studies will analyze several depot concepts and their effect on technology requirements. Coordination, in these efforts, with the Office of Exploration and the Office of Space Station will insure consistency of these depot concepts with current agency planning.

Using the OAST-sponsored report, "On-Orbit Fuels Depot Technology Roadmap," (Reference 2) as an initial point of departure, the technologies identified as high criticality and low maturity will be assessed in more detail. This assessment will entail more specific definition of the technology requirements levied by a depot system, contact with discipline experts to assess state-ofthe-art, technology development program required, and estimates of schedules and program costs.

4.5 Project Planning and Documentation

4.5.1 Pathfinder Program Plan

The Pathfinder Program Plan has been developed by the NASA Program Manager for Pathfinder.

4.5.2 Cryogenic Fluid Depot Program Plan

The Cryogenic Fluid Depot Program Plan has been developed by the Program Manager for the Cryogenic Fluid Depot who is resident in the NASA Headquarters OAST Propulsion, Power and Energy Division (Code RP).

4.5.3 Cryogenic Fluid Depot Project Plans

This plan constitutes the Cryogenic Fluid Depot Project Plan.

4.5.4 Memoranda of Understanding

The Memorandum of Understanding prepared by NASA Headquarters Codes R and M which describes the role of MSFC in the cryogenic fluid management technology development is attached as Appendix A.

4.6 Reporting

The Technology Project Manager will conduct periodic reviews with the OAST Program Manager. These reviews will assure that planned key milestones are achieved, that OAST is informed as to program status and resources expanded and required. The content and format of the periodic reviews are as follows.

4.6.1 Monthly Reporting

A written listing of monthly accomplishments will be compiled and distributed by the Technology Project Manager to the appropriate NASA Headquarters management personnel and to the matrix organizational support staff.

4.6.2 Quarterly Reporting

Every quarter the Project Management Information and Control System (MICS) method of management reporting will be used to record the progress of the program and report program status to NASA Headquarters and to the senior staff of all participating NASA centers. The reporting system will provide selected information required to ensure accountability for status, indicates trends, establishes control of schedule actions and changes, depicts manpower and illustrates funding requirements as well as the costs applicable for program management. Each quarterly report will cover all significant program aspects, including technical progress and management areas such as funding and procurement. Emphasis will be placed on defining problem areas in a timely fashion and applying necessary measures to resolve them. The compiling and distribution of the MICS report will be the responsibility of the Technology Project Manager.

4.6.3 Annual Reports

Two annual reviews will be held. A mid term review will be held yearly to present project accomplishments to date. Additionally, following the annual RTOP submittal a formal summary presentation will be made to OAST personnel indicating prior year accomplishments versus plans and

4.6.3 Annual Reports (continued)

upcoming year plans. At the same presentation, a more detailed technical review of a selected topic or topics in the program may be presented as requested. The formal presentation will be the responsibility of the Technology Project Manager.

4.7 Advisory Committees and Working Groups

4.7.1 Cryogenic Fluid Management Technology Coordinating Committee (CFMTCC)

A group of NASA top-level technical managers have been assembled as the Cryogenic Fluid Management Technology Coordination Committee. They are formed under the direction of the Directors of the Propulsion, Power and Energy Division and Flight Projects Division of OAST and the Director of Advanced Program Development in OSF. The Committee shall conduct annual reviews with the objective of reviewing and assessing current year progress and accomplishments in the ongoing cryogenic fluid management program efforts at the NASA LeRC and MSFC. Additionally, the Committee will coordinate the OAST and OSF cryogenic fluid management programs to assure development of future Agency technology needs. A copy of the charter for the CFMTCC is attached as appendix B.

4.7.2 Cryogenic Technology Advisory Group (CTAG)

A group of distinguished experts in the cryogenic technology arena have been assembled as the Cryogenic Technology Advisory Group. They are formed under the direction of the Directors of the Propulsion, Power and Energy Division and the Flight Projects Division of OAST.

4.7.2 Cryogenic Technology Advisory Group (CTAG) (continued)

The group's function is to assure that the cryogenic fluid management task (1.2) of the Cryogenic Fluid Depot Project addresses technology issues pertinent to future NASA missions. An additional responsibility of the group will be to attend major reviews of LeRC contractual efforts and provide technical critique and comments to the Cryogenic Fluid Depot Project Manager in a timely manner. In this role, the group's technical critique will focus on the evaluation of contractor analytical and experimental techniques to assure that technical objectives are not comprised. A copy of the charter for the CTAG is attached as appendix C.

5.0 TECHNICAL PLAN

5.1 Overview

5.1.1 Summary of Deliverables

The deliverables specified to date under this Plan are listed in figure 1-2 for the first five years of the project (FY 1989-1993).

5.1.2 Fiscal Year 1989 Schedule and Milestones

The fiscal year 1989 schedule and milestones can be found for each work breakdown structure task. For task 1.1, system integration, see figure 5-1 and for task 1.2, cryogenic fluid management see figure 5-2. Schedules and milestones for tasks 1.3 through 1.6 will be generated based on the results of the studies performed under task 1.1, system integration.

5.1.3 Five Year Schedule and Milestones

Figure 1-2 provides a schedule for the first five years of the project (FY 1989-1993) and table 1-1 provides a milestone table for the same time period.

5.1.4 Technology Performance Objectives

A systematic approach to the identification of technology issues of a space-based cryogenic fluid depot will begin with the definition of the system requirements. These requirements are generated by the missions which a depot will support. These requirements will be collected from the user organizations (Codes C, E, M, S, and Z) and catalogued in a data base. The requirements are expected to include at least the types and quantities of cryogenic fluids required, the location in which they are required, the duration of the storage time, reservicing frequency, etc.

For each technology discipline area tentatively identified in the work breakdown structure of figure 4-1, a technology development plan shall be prepared. It will consist of a series of time-phased activities to yield the desired technology. Each plan may include analysis, ground-based experimentation and identification of space flight experimentation as appropriate. The plans will also identify other technology work which is ongoing in other funded programs which may be appropriate for the depot.

In the area of cryogenic fluid management, task 1.2, the technology deficiencies have already been identified. This was accomplished via a Cryogenic Fluid Management Workshop held at LeRC in April 1987, with the objective of identification of future needs for technology that will allow the

5.1.4 Technology Performance Objectives (continued)

efficient and effective management of subcritical cryogenic fluids in the low-gravity space environment. Additionally, the workshop participants were asked to identify those technologies which will require in-space experimentation and those which can be developed by ground-based experimentation. More than 100 individuals attended the workshop with 24 nongovernment organizations, NBS, AFAL, AFWAL and all NASA installations except KSC being represented (see Reference 1).

There was a consensus reached by the workshop participants in terms of identification of technologies which are required. Following the technology identification, an assessment was made with regard to the current state of readiness of the technology and where the technology needed to be in order to confidently design an on-orbit cryogenic fluid depot. Each identified technology was also assessed in terms of criticality for the depot. The definition of technology readiness levels, technology criticality and the readiness level required for system design are shown in charts 5-1 through 5-4 for all identified cryogenic fluid management technology. A similar approach will be followed for technologies other than fluid management.

5.1.5 Technology Readiness Objectives

Critical components, not currently available for a cryogenic fluid depot will be designed, built, and tested. They will be characterized as to performance, safety, realiability and quality assurance. They may be incorporated into the one-g breadboard or into flight experiments as appropriate.

5.1.5 Technology Readiness Objectives (continued)

A high fidelity Depot model will be tested in a simulated space environment to establish overall system thermal performance. The approximately half-scale model will incorporate thick multilayer insulation, multiple vapor cooled shields which include para-to-ortho conversion of the vent gas, low thermal conductivity components and possibly a refrigeration subsystem. The Depot system demonstrates will provide a quantified assessment of the effectiveness of integrating several advanced technology thermal control concepts into a single unit.

5.2 System Integration

5.2.1 Objectives

The system integration work breakdown structure element will define operational cryogenic fluid depot requirements, provide conceptual designs optimized through systems analysis trade studies, determine system integration requirements and concepts, and define system test elements and requirements.

Operational fluid depot concepts will be determined on the basis of agency space operations needs and will incorporate the needs and functions of all of the relevant Headquarters' codes. On this basis, the cryogenic fluid depot technology needs, relevant to Code R, and in particular the Pathfinder Program will be determined.

5.2.2 Technical Approach

The systems integration work package will be implemented by a combination of in-house efforts (LeRC in coordination with other NASA centers), contracts, and support service contractors. Two relevant contract efforts are now being initiated that will support the systems integration element of the Cryogenic Fluid Depot Program. These are a short term (less than a year) task to define Space Station depot fluid requirements and a long-term (5 year) task order contract available for studies relative to all of the objectives of WBS 1.1. The first study is a Code ST funded effort, and the second will leverage funds from Code S, T, Z, and possibly others. These studies are further described below:

- A Code ST funded effort to conduct an inventory of all fluids and fluid usage expected to be associated with the Space Station during its evolutionary phase. This will include Code Z propellant requirements for manned lunar and Mars missions staged at the Space Station. This contract will be initiated in the first quarter of FY89 and will be concluded in time to provide inputs to the PDR of the SSP beginning in November 1989. It is approximately one man-year level of effort. The Space Station fluids inventory information developed here will be one part of the initial systems requirements information developed under Mission Studies.

- The second study effort initiated in the third quarter FY89 will be a much larger level of effort or task order-type contract extending over a period of five years, approximately 40,000 man-hours of labor, and will utilize funds from Codes R, S, Z, and possibly others to do depot-related study tasks. The scope of this effort will include most tasks of the systems integration task. The rationale for a long-term task order contract is to be able to respond promptly to depot study needs as they become defined. At this point, it is not possible to specify all of the depot issues well enough to write a comprehensive depot statement of work. As issues become defined, new requirements are identified, and as the need for particular trade studies emerges, tasks can be levied as appropriate. By consolidating various codes funding, economies of scale of a much larger contract may be gained. Also, a further advantage lies in having Codes R, S, and Z depot interests represented in a single contractor managed by one NASA organization, thus allowing these interests to be closely integrated. The task order contract described above is expected to be a primary vehicle for accomplishing the objective of Section 5.2.1. Other contract and in-house efforts will be initiated as needed.

5.2.3 Description

The task and subtask work breakdown structure for system integration is shown in figure 4-2. A description of each element in the work breakdown structure is presented below.

<u>5.2.3.1 System Requirements (task 1.1.1)</u> - The systems requirements portion of the WBS will consist of two subtasks:

- Mission studies to identify the missions a cryogenic fluid depot would likely support and, therefore, characterize the usage of a depot, i.e., what types of fluids and how much, frequency of transfer, resupply, and other usage characteristics and issues (e.g., safety) relevant to design.

- System concepts responding to the requirements identified in (1).

<u>5.2.3.1.1 Mission Studies (subtask 1.1.1.1)</u> - Assessments of the potential missions and applications requiring the services of a cryogenic fluid depot will be done. NASA mission models, appropriate databases, and surveys of the user community will be explored for cryogenic fluid needs. Prior and ongoing studies will be identified and results utilized where appropriate. Documented requirements will be obtained from Codes C, E, M, S, and Z. Codes C and E will be assessed for cryogenic fluid needs associated with low-gravity experimentation, materials processing, and scientific instrument and satellite resupply needs, S for fluid accommodation and management needs identified and planned for to date, M in relation to STV requirements, and Z for the manned lunar and Mars case study requirements. A number of studies have been sponsored by these codes containing information relevant to their in-space cryogenic fluid requirements. These and other ongoing studies will be identified and results utilized where appropriate. Specifically, work has been sponsored by MSFC concerning STV refueling requirements, LaRC for in-space fueling requirements in support of Code Z planetary mission case studies, and a Code ST sponsored study done by MCDD in which was developed an Evolutionary Space Station Mission model containing fluid requirements. Several other related studies have been done and others are planned.

The mission studies subtask of the WBS will be accomplished by a combination of contracting and in-house efforts and will leverage other Headquarters codes funds. The two contracting efforts (Section 5.2.2) planned to be initiated in FY89 will address cryogenic depot requirements. The first effort will define cryogenic depot requirements involving the Space Station. This information will be available as input to the task order contract, updated as necessary, and the effort broadened to address mission requirements not directly involving the Space Station infrastructure such as potential Code Z needs for fluid transfer at Earth/Moon libration points, in lunar orbit or on the lunar surface, in Mars orbit, or at one of Mars moons and possibly other locations. These requirements will form the basis for formulating the systems concepts of the WBS, subtask 1.1.1.2.

<u>5.2.3.1.2 System Concepts (subtask 1.1.1.2)</u> - Based on the requirements identified by the mission studies, several alternative depot concepts will be formulated. Initially, these concepts will be preliminary in nature and provide the basis for the systems analysis and assessments (WBS task 1.1.2). These studies will identify the optimum techniques and technologies that will lead to the definition of the final or baseline depot concepts. The initial depot concepts will be formulated after a baseline set of requirements has been defined in section 5.2.3.1. Prior depot definition work will be drawn upon to the extent of its utility (e.g., work done by LaRC and MSFC). Initially an array of depot concepts responding to the same requirements, but employing alternative techniques and technologies (e.g., hard attached to Space Station, tethered, co-orbiting platform, various levels of advanced technologies, A&R versus manned, etc.) will be formulated. This will provide

a perspective for initiating WBS task 1.1.2, systems analysis and assessments. The task order contract described in section 5.2.2 will be utilized extensively for conducting this WBS task.

5.2.3.2 System Analysis and Assessments (task 1.1.2)

This WBS task will serve to identify relevant depot-related issues, efficient and cost effective ways of performing depot functions, high payoff advanced technologies needed, and high leverage approaches having the highest overall positive impact on NASA long-range mission plans.

5.2.3.2.1 System Requirements (subtask 1.1.2.1) - This WBS subtask will serve to determine the functional and subsystem requirements (the technical ways in which the depot and its subsystems must perform) in order to satisfy the user requirements identified in WBS task 1.1.1. This will include all aspects of depot configuration, operation, and performance such as capacities, mass, stability, communications, power, safety, and interface with users.

5.2.3.2.2 Payoff/Tradeoff Assessments (substask 1.1.2.2)

In this WBS subtask, the relative merits of alternative subsystem and technique options will be explored with respect to the system concepts. These trade studies will serve to identify the high payoff items and most effective depot concepts. Trade studies are expected to encompass all aspects of depot configuration, design, subsystems, technologies, operations, safety issues, costs, and others. In particular, the trade studies will serve to identify high payoff, enabling, and critical technologies.

5.2.3.2.3 Optimization Studies (subtask 1.1.2.3) - This WBS subtask will integrate the results of the trade studies of the previous subtask in optimum combination to achieve the most effective (cost and performance) depot concepts.

5.2.3.2.4 Logistics Analysis (subtask 1.1.2.4) - This WBS subtask will assess the logistic requirements for depot construction and resupply. The capabilities (payload weights, volumes) of advanced launch vehicle concepts (e.g., Shuttle C, ALS, etc.) will be assessed for their impact on depot configuration, implementation, and operations. Assumptions concerning the usage of particular launch vehicles will impose constraints on depot concept configuration and operations. This in turn may emphasis requirements for particular technologies which will be illuminated in this study process. On the other hand, particularly attractive operational cryogenic fluid depot features that would be enabled or significantly enhanced by certain launch vehicle characteristics, could be an important input into launch vehicle planning.

This subtask is closely related to WBS subtask 1.1.2.2, "Payoff/Tradeoff Assessments" in determining depot configuration and operation sensitivies to assumptions concerning supporting infrastructure elements and to WBS 1.1.2.3, "Optimization Studies" in determining the optimum combination of elements to achieve the most productive depot concepts.

5.2.3.2.5 Performance Predictions (subtask 1.1.2.5) - In this WBS subtask, analyses will be performed to predict the operational performance of the depot concepts. The behavior and response of all depot operational parameters during servicing operations will be determined. Any adverse responses or unacceptable constraints will be determined here. The results of this WBS subtask will be used to refine and improve the baseline concepts.

<u>5.2.3.3 Subsystem Integration (task 1.1.3)</u> - This WBS task will define how all major depot elements, subsystems, and components may be integrated into an operational cryogenic fluids depot. After having determined the preferred depot concept(s) through the concept formulation/ trade study process, a detailed analysis of how all the subsystems may be integrated into a smoothly functioning whole will be performed. Particular requirements to assure proper integration and functioning will be determined.

<u>5.2.3.3.1 System Concepts (subtask 1.1.3.1)</u> - The iterative interaction of WBS tasks 1.1.1 and 1.1.2 will result in selection of promising concept(s) for detailed assessment. These concepts will have been defined to the subsystem level and subsystem performance requirements determined.

<u>5.2.3.3.2 Integration Analysis (subtask 1.1.3.2)</u> - This WBS subtask will determine how all the depot elements may be integrated in a properly functioning manner. All subsystem functions and interrelationships will be analyzed to ensure compatibility with other on-board subsystems and user interfaces.

An analysis of how the selected depot concepts could be implemented will be made. This will include the sequence of events necessary to establish a depot, e.g., when and how subsystems are delivered and mated, flights and flight frequencies required, and the general outline of the timeline and resource requirements of a depot implementation program.

5.2.3.3.3 Integration Requirements (subtask 1.1.3.3)
The integration analysis of the previous subtasks will determine the particular requirements of the integration of depot subsystems and other operational elements. Appropriate interfaces, safety requirements, and timeline of events will be specified.

5.2.3.4 System Test (task 1.1.4) - This WBS task will establish the necessary ground and flight experiments, test bed definition, and test program plan.

5.2.3.4.1 System Test (subtask 1.1.4.1) - This WBS subtask will establish the necessary test requirements for cryogenic depot-related systems, subsystems, and components. Those elements and configurations that may be sufficiently tested on the ground in a one-g environment will be identified as well as those requiring in-space testing. Required test conditions and parameters will be established. Test plans will be established for both ground and space testing. In addition, a preliminary design of a ground test article will be performed.

5.2.3.4.2 Ground Test Bed (subtask 1.1.4.2) - A ground test bed article incorporating the integrated subsystems and test features that may be ground tested, as identified in the previous subtask, will be designed..

5.2.3.4.3 Flight Experiments (subtask 1.1.4.3) - The space test requirements identified in the system test (subtask 1.1.4.1) will be used to formulate specific experiments and a flight test program plan.

5.2.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for the system integration task (1.1) are shown in figure 5-1.

5.2.5 Resource Allocation

Resources required for the first five years of the system integration task (1.1) are shown in table 5-1.

5.3 Cryogenic Fluid Management (Task 1.2)

5.3.1 Objectives

The work for task 1.2, cryogenic fluid management, will be performed by the LeRC Cryogenic Fluids Technology Office (CFTO) under technical direction provided by the Technology Project Manager.

A Cryogenic Fluid Management Technology Workshop was held under sponsorship of the Cryogenic Fluids Technology Office during April 1987, in Cleveland, Ohio. The major objective of the workshop was to identify future NASA needs for technology that will allow the efficient and effective management of subcritical cryogenic fluids in the low-gravity space environment.

Thirty-two technologies were identified with varying degrees of criticality. They were grouped in the six major categories of (1) liquid storage, (2) liquid supply, (3) liquid transfer, (4) fluid handling, (5) structures and materials, and (6) advanced instrumentation. These form

5.3.1 Objectives (continued)

the basis of work breakdown structures described in figures 4-3a through 4-3f. Some of the technology needs are being developed by other NASA Centers (See Charts 5-1 through 5-4) and the Air Force with support of academia and industry. The status of these activities are being tracked by the Principal Investigator assigned to the Cryogenic Fluids Technology Office.

Several technology items were designated as enabling, headed by the technologies associated with on-orbit fluid transfer (tank chilldown and no-vent fill) and those associated with the on-orbit pressure control (thermodynamic vent systems and fluid mixing). These technologies and others are being addressed by the LeRC Cryogenic Fluids Technology Office.

5.3.2 Technical Approach

To accomplish its mission, a comprehensive cryogenic fluid management technology plan was developed by the Cryogenic Fluids Technology Office. The basic elements of the plan are: analytical model development and validation, ground-based testing and in-space experimentation requirements.

Extensive analytical models are being developed by the LeRC staff and under contract to predict the fluid and thermal behavior of cryogenic fluids in both the low-gravity and zero-gravity environment. These computer models will be documented, integrated into an analytical data base and distributed to the user community. The services of co-investigators have been obtained under contract, to aid in the development of several of the cryogenic technologies.

5.3.2 Technical Approach

Ground-based testing will be performed in several LeRC cryogenic facilities; (FML, CRL-13, and K-Site) as part of a basic research and technology program with the objective of developing a fundamental understanding of important technological processes, providing normal gravity data points for comparison with flight data, and for providing limited verification of analytical models. Certain technologies for the storage system can be developed in total by ground-based testing.

In-space experimentation for 17 of the 32 technologies is required to provide essential low-gravity environment to verify the prediction of the analytical and numerical models, provide subscale system demonstrations, and validate the performance of several cryogenic system components. The Cryogenic Fluids Technology Office will integrate as many technology experiments as practical into its in-space experimentation effort. Flight hardware will be designed and fabricated that is capable of being carried into low-earth orbit to conduct low-gravity cryogenic fluid management experiments. The preferred flight hardware is a free-flying spacecraft; however, precursory and/or supplementary shuttle-based experiments also may be flown. The free-flying spacecraft termed COLD-SAT would employ liquid hydrogen as a test fluid, be launched on an expendable launch vehicle (ELV), and be designed for a 6 to 24 month life on orbit. Funding for the flight experimentation is currently beyond the scope of the funding planned for the Cryogenic Fluid Depot Element. It should be emphasized that without adequate funding for flight experimentation much of the technologies required for the Cryogenic Fluid Depot will not be developed to the required technology readiness level.

5.3.2 Technical Approach (continued)

All of the technology developed by this plan will be documented and incorporated into the Cryogenic Fluid Depot design data base.

5.3.3 Description

The following will discuss the plans for each of the three major elements of the cryogenic fluid management task (1-2) and will indicate the LeRC facilities which will be utilized in ground testing. The three major elements are: (1) analytical model development and validation, (2) ground-based testing (including system demonstrations), and (3) in-space experimentation.

5.3.3.1 Analytical Model Development and Validation - Analytical models describing the key processes expected to influence the storage, supply and transfer of subcritical cryogenic fluids in the low-gravity space environment will be developed. These analytical models will be validated/ verified by comparison with both ground and space flight experiment data and made available to the aerospace community. The analytical modeling effort consists of: 1) prototype modeling, primarily performed in-house, in which stand-alone models are developed from basic principles; 2) complementary modeling, primarily performed via grant, contract and interagency agreements and 3) integrated system-level modeling, primarily performed in-house, in which the prototype and complementary analytical models are combined into an integrated system-level model which can be used to predict low-gravity fluid and thermal behavior of future in-space cryogenic storage, supply and transfer systems.

5.3.3.1.1 In-House Prototype Modeling - Analytical models currently being developed in-house include thermodynamic childown, no-vent fill bulk liquid transport, no-vent fill interface kinetics and transient childown. A description of each of these models and their use is provided in Table 5-2. The thermodynamic childown model can provide first order estimates of tank childown requirements in terms of predicting the target temperature to which the tank must be chilled prior to initiating a no-vent tank filling and will provide a prediction of the mass of cryogenic liquid required for childown of the tank. The transient chill-down model will extend this thermodynamic childown model to include the transient effects and will be capable of treating variable heat leaks at the tank wall. The no-vent fill bulk liquid transport model can determine the initial receiver tank pressure rise caused by flashing of the incoming cryogen and will predict tank pressure use during no-vent fill. While there is no available experiment data for comparison it appears to generate anticipated and realistic pressure trends. The no-vent fill interface kinetics model will predict the transient responses of pressure during the no-vent fill process. Both of the no-vent fill models will be improved by the addition of additional nodes, refining of the free surface interface configuration for low-gravity and the inclusion of unproved models for liquid droplet spray. The childown model requires refinement of the wall-to-vapor heat transfer model. A new analytical model will be initiated to model transient pressure control processes.

5.3.3.1.2 Complementary Modeling - LeRC has sponsored the development of several analytical models: NASA-VOF2D, NASA-VOF3D and SOLA-ECLIPSE. NASA-VOF2D was developed by the Los Alamos National Laboratory (LANL) for LeRC and is documented in Los Alamos Report LA-10612-MS. It is available from the National Energy Software Center at the Argonne National Laboratory. It solves the 2-D Navier-Stokes equations in either cartesian or cylindrical coordinates, includes the effects of surface tension and wall adhesion, has the capability of variable mesh size and can treat multiple complex free surfaces. It has been used to study low-gravity reorientation, propulsive settling and tank draining. NASA-VOF3D was also developed by the LANL for LeRC and is documented in Los Alamos Report LA-11009. It is also available from the National Energy Software Center. Its primary purpose was to extend the NASA-VOF2D to three dimensions. This permits the study of liquid sloshing and off-axis propellant settling.

SOLA-ECLIPSE was developed by Washington University at St. Louis for LeRC. It 1) includes the energy equation in the VOF2D model, 2) adds a K E turbulence model and the capability of adding inflow to the tank and 3) can treat the thermodynamics of the ullage. It permits examination of problems associated with pressure control and fluid mixing. Table 5-3 describes each of the complementary models and indicates their utility.

Work is continuing on improving the capability of these analytical models. In NASA-VOF3D, the plan is to investigate swirl flows (to permit the study of no-vent fill and chilldown with tangential spray nozzles) and in SOLA-ECLIPSE the intension is to improve the heat transfer model at the liquid vapor interface by including the results of experimental and analytical work currently being funded at the MIT.

5.3.3.1.2 Integrated Modeling (CryoTran) - An integrated, system-level analytical model will be developed which combines all prototype and analytical models as well as the SINDA thermal analyzer in a computer code called CryoTran. The CryoTran code will be capable of analyzing complex subcritical cryogenic storage, supply and transfer systems. A baseline set of 20 problems which CryoTran will be capable of analyzing has been established. These 20 problems and the pre and postprocessor work can be grouped into nine work packages when key fluid and thermal processes and solution techniques are used. These nine work packages are listed in Table 5-4.

Currently, design requirements for the preprocessor for CryoTran are being defined, and postprocessing is available from the existing SINDA and VOF codes. In the heat exchange work package extensive modeling has been performed with SINDA and some preliminary modeling has been done with SOLA-ECLIPSE. In the insulation work package, SINDA has been used as a driver for other codes. In the thermodynamic work package, prototype models are nearing completion. In the VOF2D interface package, requirements are being defined. In the liquid acquisition device work package, extensive modeling has already been completed while in the fluid dynamics work package and the 3-D Spray work package, VOF3D prototype development has been initiated.

Charts 5-1 through 5-4 present a summary listing of the 32 identified cryogenic fluid management technologies grouped in the six major categories of (1) liquid storage, (2) liquid supply, (3) liquid transfer, (4) fluid handling, (5) structures and materials, and (6) advanced instrumentation.

The specific CryoTran work package which addresses each technology is shown under Analytical Modeling - CryoTran, in the charts.

<u>5.3.3.2 Ground-Based Testing</u> - It is convenient to group the ground-based testing into three general categories: (1) precursory experimentation, (2) storage and transfer system tests and (3) subscale depot system demonstration. Charts 5-1 through 5-4 show which of the 32 cryogenic fluid management technologies are being addressed in each of the three general categories of ground experiments. These are shown under 1-G Experimentation. The LeRC facilities utilized for testing are specified in the charts. Those technologies which can be completely developed by ground-based testing are also identified in charts 5-1 through 5-4.

In order to determine the levels of maturity of a technology (i.e., "technology readiness") it is possible to define eight technology readiness levels as shown in Table 5-5. Likewise, the importance or "criticality" of technology can be assessed by defining the two technology criticality levels shown in Table 5-5.

Using these criteria, it is possible to develop a listing giving an indication of the importance of the individual cryogenic fluid management technologies in performing future NASA missions such as the cryogenic fuel depot.

The listing is shown on charts 5-1 through 5-4 under Technology Levels. The current state-of-the-art of each technology versus the technology level goal is listed under-Readiness SOA/goal. The criticality is also shown for each technology on the charts.

<u>5.3.3.2.1 Precursory Experimentation</u> - Precursory experimentation has the objective of: (1) providing a fundamental understanding of certain individual physical processes of important in low-gravity cryogenic fluid management; (2) providing a basis for modification and partial validation of analytical models; (3) allowing initial study of fluid storage, supply and transfer techniques (chilldown, no-vent fill, mixing, pressurization, stratification/destratification, pressure control); and (4) permitting preliminary evaluation and characterization of typical cryogenic system components (visco-jets, Joule-Thompson devices, spray nozzles, and other instrumentation). Precursory experiments will primarily be conducted either with liquid nitrogen (in CRL-13, see section 7.2.3) or with small quantities of liquid hydrogen (in FML, see Section 7.2.2) or in the Zero Gravity Facility with simulant fluids (See section 7.2.4). Additionally, some contracted testing may be also performed as needed (such as at MIT or NBS). For each experiment set, an experiment requirements document will be developed.

Only current firm test requirements are planned through FY90. It is likely that additional testing will be required following results of this initial series of tests. In estimating resource requirements, testing has been assumed to continue at essentially constant level through FY95 although specific test plans have not been firmed up beyond FY90. As new test requirements become available, the schedules will be modified accordingly.

5.3.3.2.2 Storage and Transfer System - Storage and transfer system experimentation using cryogenic fluids has the objectives of, (1) establishing an adequate normal gravity data base where either none currently exists or the data base is too limited to be of value, (2) preliminary or partial validation of the analytical models discussed in section 5.3.3.1, (3) reducing the parametric variation which is required in flight experiments, (4) establishing preliminary system operational procedures and (5) developing the required cryogenic fluid management technology in those areas in which the gravitational influence is slight or nonexistant. These experiments will primarly be conducted using liquid hydrogen in the K-Site facility described in Section 7.2.1. For each experiment set, as was the case for the precursory experimentation, an experiment requirements document will be prepared and appropriate text procedures will be developed.

Experiments to be performed include: transfer line chilldown, tank chilldown, no-vent fill, thermal stratification, condensation/evaporation at the liquid vapor interface, jet induced mixing, passive and active thermodynamic venting, advanced instrumentation evaluation (mass flow/quality metering, mass gauging, and leak detection), liquid acquisition device degradation, combined foam/MLI thermal performance, tank pressurization and thermal subcooling.

As was the case for the precursory experimentation, tests at K-Site while anticipated to continue through approximately 1993 are only planned through FY90.

5.3.3.2.3 Subscale Depot System Demonstration - A high fidelity Depot model will be tested in a simulated space environment to establish overall system thermal performance. The approximatly half-scale model will incorporate thick multilayer insulation, multiple vapor cooled shields which include para-to-ortho conversion of the vent gas, low thermal conductivity components and possibly a refrigeration subsystem. The Depot system demonstrations will provide a quantified assessment of the effectivness of integrating several advanced technology thermal control concepts into a single unit.

5.3.3.3 In-Space Experimentation - In-space experimentation for 17 of the identified 32 cryogenic fluid management technologies is required to provide essential low-gravity environment to verify the prediction of the analytical and numerical models, provide subscale system demonstrations, and validate the performance of several cryogenic system components. The Cryogenic Fluids Technology Office will integrate as many technology experiments as practical into its in-space experimentation effort. The preferred flight hardware is a free-flying spacecraft; however precursory and/or supplementary shuttle based experiments may also be flown. As mentioned previously, the funding requirements for these flight exeriments exceed the funding currently available in the Cryogenic Fluid Depot Element of Pathfinder.

A concept for the free-flying spacecraft named COLD-SAT, (Cryogenic On-orbit Liquid Depot-Supply, Acquisition, Transfer) is being developed through the award of three Feasibility Study Contracts to major aerospace companies and LeRC In-House Design Team. Two classes of experiments, class I and class II based on the criticality of each technology was defined. All class I experiments are planned to be flown on COLD-SAT. Class II experiments will be performed on COLD-SAT if they can be accomodated. Charts 5-1 through 5-4 depict under the heading, In-Space Experimentation, the class rating of the technology to be flown on COLD-SAT and, the planned STS experimentation. The charts also indicate if in-space experimentation is required for development of the technology.

5.3.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for the cryogenic fluid management task are shown in figure 5-2.

5.3.5 Resource Allocation

Resources required for the first five years of the cryogenic fluid management task (1.2) are shown in table 5-6. Note that these resources do not include resources required for flight experimentation.

5.4 Depot Operations (Task 1.3)

Depot Operations is a tentative technology development activity for the Cryogenic Fluid Depot. It was identified as a potential area for technology development in prior studies and workshops (refs. 1 and 2).

5.4.1 Objectives

Potential work performed for task 1.3, depot operations will be to develop the technology base required for a cryogenic fluid depot to support its primary operational function of storing and supplying cryogenic propellants and other fluids for NASA/DOD launch systems (STV, lunar, Mars, etc.), satellites, and Space Station.

5.4.2 Technical Approach

Initial studies will be performed in task 1.1 system integration, to identify potential future cryogenic fluid user needs and requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology roadmap will be prepared which defines the criticality of the identified technology and assesses the current state of technology readiness and the state of technology readiness required for the development of an operational on-orbit cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These roadmaps will be used to lay out a time-phased technology program.

5.4.3 Description

Potential technologies relevant to the "Depot Operations" WBS task are those concerning the general "houskeeping" functions of the depot and with enabling the depot to perform its necessary functions. Examples may include

5.4.3 Description (continued)

attitude and thermal control, station keeping, vibration control, and those relating to propellant manufacturing and vehicle servicing, if applicable.

Potential specific technologies related to depot operations may include the following:

- Automated Operation/Robotics
- Automated Vehicle and Payload Processing
- Large Flexible Structure Control
- Space Power (500 KW)
- Artificial Gravity Generation
- Attitude Control by Momentum Management
- Mass Properties Management
- Oxygen/Resistojet (Propulsion)
- Supercritical Tanks
- Vibration Control
- On-Orbit Assembly of Insulation
- On-Orbit Tank Assembly
- Water Electrolysis
- Attitude Control by Superconductor

5.4.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for task 1.3, depot operations will be generated based upon the results of the studies performed under task 1.1, system integration.

5.4.5 Resource Allocation

The resource allocation for task 1.3, depot operations will be generated based upon the results of the studies performed under task 1.1, system integration.

5.5 Structures and Materials (Task 1.4)

Structures and Materials is a tentative technology development activity for the Cryogenic Fluid Depot. It was identified as a potential area for technology development in prior studies and workshops (refs. 1 and 2).

5.5.1 Objectives

Potential work performed for task 1.4, structures and materials will be to identify cryogenic fluid depot-unique technology requirements for structures and materials that are beyond the current state-of-the-art, to assess the criticality of any technology shortfalls to the depot program, and to develop an advanced development plan that assures technology readiness in a time frame consistent with depot planning.

5.5.2 Technical Approach

Initial studies will be performed in task 1.1 system integration, to identify potential future cryogenic fluid user needs and requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology roadmap will be prepared which defines the criticality of the identified technology and assesses the current state of technology readiness and the state of technology readiness required for the development of an operational on-orbit cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These roadmaps will be used to lay out a time-phased technology program.

5.5.3 Description

The unique technical challenges associated with a structure of several hundred meters in length supporting tanks containing millions of pounds of cryogenic fluids may include technology development in:

- Tank structural integrity
- Coatings and sealants
- Long-life space environment materials and components
- Micrometeriod/debris protection
- Composite vacuum jackets

5.5.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for task 1.4, structures and materials will be generated based upon the results of the studies performed under task 1.1, system integration.

5.5.5 Resource Allocation

The resource allocation for task 1.4, structures and materials will be generated based upon the results of the studies performed under task 1.1, system integration.

5.6 Orbital Operations and Logistics (Task 1.5)

Orbital Operations and Logistics is a tentative technology development activity for the Cryogenic Fluid Depot. It was identified as a potential area for technology development in prior studies and workshops (refs. 1 and 2).

5.6.1 Objectives

Potential work performed for task 1.5, orbital operations and logistics will be to provide the technology base that will assure routine utilization of a cryogenic fluid depot by the NASA space fleet and the effective functional support required for the depot facility.

5.6.2 Technical Approach

Initial studies will be performed in task 1.1 system integration, to identify potential future cryogenic fluid user needs and requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology roadmap will be prepared which defines the criticality of the identified technology and assesses the current state of technology readiness and the state of technology readiness required for the development of an operational on-orbit cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These roadmaps will be used to lay out a time-phased technology program.

5.6.3 Description

Typical orbital operations scenarios involving utilization of a cryogenic fluid depot will be generated and the associated logistics requirements will be defined. From these orbital operations/logistics models, those activities determined to require technologies beyond state-of-the-art will be catalogued. Technology areas that may be addressed will include:

- Advanced assembly techniques
- Advanced EVA suit
- Advanced/autonomous rendezvous techniques
- Artificial intelligence for proximity operations
- Expert systems
- Automated logistics management

5.6.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for task 1.5, orbital operations and logistics will be generated based upon the results of the studies performed under task 1.1, system integration.

5.6.5 Resource Allocation

The resource allocation for task 1.5, orbital operations and logistics will be generated based upon the results of the studies performed under task 1.1, system integration.

5.7 Safety (Task 1.6)

Safety is a tentative technology development activity for the Cryogenic Fluid Depot. It was identified as a potential area for technology development in prior studies and workshops (refs. 1 and 2).

5.7.1 Objectives

Potential work performed for task 1.6, safety will be to develop the technologies necessary to assure the safe and quality-assured operation of a cryogenic fluid depot.

5.7.2 Technical Approach

Initial studies will be performed in task 1.1 system integration, to identify potential future cryogenic fluid user needs and requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology roadmap will be prepared which defines the criticality of the identified technology and assesses the current state of technology readiness and the state of technology readiness required for the development of an operational on-orbit cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These roadmaps will be used to lay out a time-phased technology program.

5.7.3 Description

The safety issues associated with the storage and handling of large quantities of potentially explosive fluids in both gaseous and liquid states will be addressed under this task. Ground operations, launch constraints and space operations will be studied. A list of the areas that may be addressed are the following:

- Leak Repair
- On-orbit Safety Specifications
- Collision Avoidance Techniques
- Health Monitoring
- Leak Detection
- Survivability/Hardness
- Debris Removal
- Emergency Jettlson/Evacuation Ops
- Nonestructive Inspection Sensors

5.7.4 Schedule of Milestones and Deliverables

The schedule of milestones and deliverables for task 1.6, safety will be generated based upon the results of the studies performed under task 1.1, system integration.

5.7.5 Resource Allocation

The resource allocation for task 1.6, safety will be generated based upon the results of the studies performed under task 1.1, system integration.

6.0 RESOURCES AND FINANCIAL MANAGEMENT PLAN

6.1 Overview

By the early 1990's analytical models describing all aspects of low gravity cryogenic fluid management (including storage, supply, and transfer) will be developed and validated as much as possible with normal gravity testing. Ground-based testing of instrumentation components and processes will be largely completed. Flight experiment definition will be completed. Concept formulation for a full-scale depot will have been completed. The resources required to achieve these results will require the minimum funding levels shown in table 6-2. The talents of NASA personnel in concert with industry and academia will be needed to meet the milestones and deliverables specified in Section 5.0, Technical Plan.

6.2 Funding Requirement

6.2.1 Fiscal Year 1989 Requirements

The funding requirements for fiscal year 1989 are shown in table 6-1.

6.2.2 Five Year Requirements

The five year funding requirements are shown in table 6-2.

6.3 Workforce Requirements

6.3.1 Fiscal Year 1989 Requirement

The NASA workforce requirements for fiscal year 1989 are shown in table 6-3.

6.3.2 Five Year Requirements

The five year NASA workforce requirements are shown in table 6.4.

6.4 Contracting Plans

The Cryogenic Fluid Depot element of Pathfinder will utilize the expertise existing in the industrial and academic community in accordance with the approach outlined in section 5. Technology R&T contracts will be let to the industrial segment. Utilization of university research talents in the area of fluid management process modeling will contribute significantly to the effort. Other government organizations such as JPL, LANL, NBS, and other NASA Centers are expected to be part of this effort through appropriate instruments. These agencies in cooperation with in-house experts, will perform the needed studies, design and hardware tests. Also, in-house R&T will be supported by SSC's as appropriate.

6.4.1 Industry

It is anticipated that the major portion of the funding to be contracted will be committed to the U.S. aerospace industries. Initially, study contracts for the system integration task (1.1) will be awarded to an aerospace corporation. The contract will evolve into the definition

6.4.1 Industry (continued)

of a baseline depot system concept. Further trade off assessments and depot system optimization studies will be required after the acceptance of the baseline depot system concept. Beyond FY93, the aerospace industry will be requested to provide a full scale cryogenic fluid depot ground test bed potentially to support a series of flight experiments through the design and fabrication of flight qualified components and subsystems unique to the Cryogenic Fluid Depot. This latter activity is dependent on appropriate funding for the flight experiments being made available through Pathfinder.

Although plans have not been formulated for the depot operations (1.3), structures and materials (1.4), orbital operations and logistics (1.5) and safety (1.6) it is anticipated that the U.S. aerospace industry will be funded to perform definition studies and participate in the evolution of these concepts into demonstration hardware (and finally into flight qualified hardware if funding is available).

6.4.2 Universities

The utilization of the university research talents are also planned for the development of the Cryogenic Fluid Depot in the cryogenic fluid management task (1.2) Several universities are involved in the development of analytical modeling of fluid and thermal processes, verification of their models through ground based testing and providing expertise in the formulation of flight experiments while acting in the role of co-investigators. Several members of

6.4.2 Universities (continued)

the academia community have been selected to serve as ad hoc members of the cryogenic fluid management advisory groups. As plans evolve for the other project tasks of the Cryogenic Fluid Depot, it is anticipated that the universities will be requested to fulfill simillar functions. The academia community maintains a body of expertise in the areas of robotics, materials, logistics and numerical analysis. Grants will be awarded for the development and demonstration of these concepts into the final design of the Cryogenic Fluid Depot.

7.0 FACILITIES PLANS

7.1 Overview

The Technology Project Manager has under his disposition the major NASA cryogenic test facilities and an extensive network of large computational capability. These resources will be utilized to (1) validate analytical models in the normal gravity environment or for short duration periods of the low-gravity environment, (2) develope the operational processes and logistics required for storage, supply and transfer of fluids, (3) investigate the performance of components and subsystems unique to the development of the depot, (4) provide a subscale demonstration of the depot concept and (5) finally assimulate all of analytical and experimental information into a cryogenic fluid depot design data base.

7.1 Overview (continued)

The facilities available to the Technology Project Manager will evolve as the requirements for tasks 1.3 through 1.6 of the work breakdown structure are defined. The laboratory and computing test areas listed in section 7.2 are those of NASA LeRC. They have been identified as necessary for the successful completion of task 1.2, cryogenic fluid management.

7.2 Laboratories and Computing

The facilities listed below are located at NASA-LeRC and will be used to accomplish task 1.2, cryogenic fluid management

7.2.1 Cryogenic Propellant Tank Research Facility (K-Site)

The K-Site test facility located at the LeRC Plum Brook Station was originally designed to conduct research programs involving the storage, pressurization and expulsion of cryogenic propellants. The facility was designed to provide a test environment that simulated all the conditions, except low gravity, that a system would likely encounter in space.

The K-Site facility consists of a 25-foot diameter spherical stainless steel vacuum chamber with an internal volume of approximately 9500 cubic feet. The chamber can be evacuated to a level of 5×10^{-8} torr with an existing liquid hydrogen cryoshroud installed and to a level of 5×10^{-7} torr with the bare chamber. Access to the chamber is through a hydraulically operated chamber door 20 feet in

7.2.1 Cryogenic Propellant Tank Research Facility (K-Site) (continued)

diameter. A cold wall, 13 feet in diameter can use either liquid nitrogen (at $-320^{\circ}F$) or liquid hydrogen (at $-423^{\circ}F$). The vacuum chamber is housed in a building having a roll-up door 29 feet wide and 39 feet high. A monorail system with a five ton handling crane is used to handle the test packages. The facility also has a totally enclosed clean room and an attached work shop.

Control systems include a back pressure boiloff control, a closed loop temperature control, a liquid hydrogen temperature control (for the cryoshroud) and an outflow/inflow control system. A linear hydraulic actuator capable of providing force vectors up to 10,000 pounds is also available but is not planned to be used.

7.2.2 Fracture Mechanics Lab

7.2.2.1 FML-4 - A 13 inch-diameter by 36-inch deep open dewar is used to contain a bath of either LH_2 or LN_2 for the testing of various probes, flow devices, and other cryogenic instrumentation. The dewar fill system and test hardware are operated remotely from the FML control room and a PC-based data system is available to record test data. The bath temperature can be set from saturation to more than $18^{\circ}R$ below saturation conditions when necessary. Other hardware available for use with the dewar includes a probe positioner which can be used for thermal shock testing probes, and air-ejector to set up downstream conditions on flow devices, and a TV camera to monitor the condition of test items submerged in the cryogenic bath.

7.2.2.2 FML-7 - Hardware which will be used for testing with liquid hydrogen at FML-7 consists of a supply dewar (11.9 ft^3) and two receiver dewars (5.72 ft^3 and 1.28 ft^3). The supply dewar is capable of providing thermal subcooling of the liquid hydrogen via an internal counter flow heat exchanger and the receiver dewars can be fitted with various internal spray systems. This series of dewars is well instrumented with temperature pressure and liquid level sensors. The dewar fill system and test hardware are operated remotely from the FML control room and a PC-based data system is available to record test data.

7.2.3 Liquid Nitrogen Test Facility (CRL-13)

The liquid nitrogen test facility in Cell 13 of Building 35 was designed to provide early ground testing of cryogen transfer techniques.

The test facility supply tank will be filled from a 500 gallon dewar located just outside the test cell. The cylindrical supply tank will hold approximately 75 gallons of LN_2. The top head of the tank is flanged to provide total access and both heads have a six-inch flanged port for the insertion of test articles or instrumentation. Two six-inch view ports are located 180^o apart on the upper portion of the tank wall for camera or visual observations.

There is one two-inch view port in the top head. A cryo-panel is attached to the lower head and the cylindrical wall to intercept any heat that leaks through the six-inch foam insulation that incapsulates the entire tank.

7.2.3 Liquid Nitrogen Test Facility (CRL-13) (continued)

Gaseous nitrogen and helium are supplied from an external high pressure tube farm for system purging and tank pressurization. A source of saturated gaseous nitrogen will be provided from a liquid nitrogen boiler.

A vacuum vent system is provided to simulate venting to space. This system can also be used to lower the pressure in the supply tank below one atmosphere.

During low flow test conditions the fluid will pass through a heat exchanger to assure total vaporization of the fluid. Flow can then be accurately measured using gas flowmeters.

A separate leg has been provided to accommodate the installation of a receiver tank at a later date. This will be a light weight (flight-type) tank to study tank chilldown and no-vent fill.

The data system is based on the LeRC ESCORT control data system. Two hundred and fifty parameters can be recorded at up to one scan per second, and they are displayed in real-time in engineering units. The ESCORT system will also supply calculated parameters and perform control and alarm functions.

Basic facility parameters such as temperature, pressure, liquid level, and flow are recorded and many channels are available for specific instrumentation required for specific tests.

7.2.4 Zero-Gravity Facility (ZGF)

The Zero-Gravity Facility consists of a concrete-lined 8.7 meter diameter shaft that extends 155 meters below ground level. A steel vacuum chamber, 6.1 meters in diameter and 142 meters high, is contained within the concrete shaft. By utilizing the Lewis wind tunnel exhaust system in series with vacuum pumps located in the facility, the pressure in the vacuum chamber is reduced to 13.3 newtons per square meter (1.3×10^{-4} atm.). Dropping a vehicle from the top of this chamber results in approximately five seconds of free-fall time.

The vehicle falls with no guides or electrical lines connected to it. The package falls in an evacuated environment, and therefore, a drag shield is not required. The residual air that is left in the drop chamber after pumpdown does produce a very low drag on the package; but this force results in an equivalent acceleration acting on the vehicle which is estimated to be no greater the 10^{-5}g.

A typical test vehicle consists of a cylindrical body where the experiment assembly, direct-current power and control systems are housed. The entire experimental package is balanced about the vertical axis prior to a drop. After preparation of the experiment is complete, the test vehicle is suspended at the top of the vacuum chamber by a support shaft (connected to the cylindrical section of the vehicle) on a hinge plate assembly. Once chamber pumpdown is completed, the vehicle is released by pneumatically shearing a bolt that holds the hinged plate in a closed position. Following the free-fall period, the vehicle is

7.2.4 Zero-Gravity Facility (ZGF) (continued)

decelerated at the bottom of the chamber in a cart filled with small pellets of expanded polystyrene. After the drop, the vacuum chamber is vented to the atmosphere and the experiment is returned to ground level.

This test facility may be used to study certain fluid dynamic problems using referee fluids such as alcohols and freons. Potential study areas include flow patterns and spray nozzle characterization and fluid mixing during tank fill. Small scale model tanks fabricated from optically clear plexiglas would be utilized to enable visual recording of data.

The ZGF also has a class 10000 clean room which can be utilized for the assembly of sensitive components.

7.2.5 Research Analysis Center (RAC)

The RAC contains several large computers (IBM, CRAY, AMDAHL) which will be used in support of analysis in areas covering fluid, thermal, structures, dynamics, etc. Programs to be run include CSAM, NASTRAN, SINDA, TRASYS, and CryoTran.

7.3 Demonstration Facilities and Testing

7.3.1 Cryogenic Propellant Tank Research Facility (K-Site)

K-Site can be used for subscale depot demonstration testing. A description of the facility can be found in section 7.2.1.

7.3.2 Test Stand 300

Test Stand 300 is located at the MSFC and is one of the six active propulsive test facilities. The test stand is located in the east test area. It is a multiposition test stand connected by underground instrumentation and control duct banks to the control and service center - Building 4561. The test stand is served by a high pressure industrial water system, stream, electrical power, high pressure gases (GN_2, GH_2, GHe, Air), - LOX or LN_2 storage and transfer systems.

Test Stand 300 is equipped with two vacuum chambers with rapid pumpdown capability to 10^{-6} torr in a 18 ft. diameter by 26.5 ft. chamber with cold walls and 10^{-3} torr in a 12 ft. diameter by 15.5 ft. chamber.

7.4 Facilities Assessment

An assessment of the facilities required for the development of the Cryogenic Fluid Depot Project will be made after the completion of the system integration subtask 1.1.1.2, baseline concept.

8.0 TECHNOLOGY TRANSFER PLANNING

The technology developed during the evaluation of the Cryogenic fluid Depot Project will be made available to the user community through a series of workshops, reviews, publications and conference presentations. As an example, in task 1.2, cryogenic fluid management several papers have been presented at AIAA conferences and two analytical codes have been documented and released to the industrial user community.

This section of the Project Plan will be expanded as the technology requirements are defined.

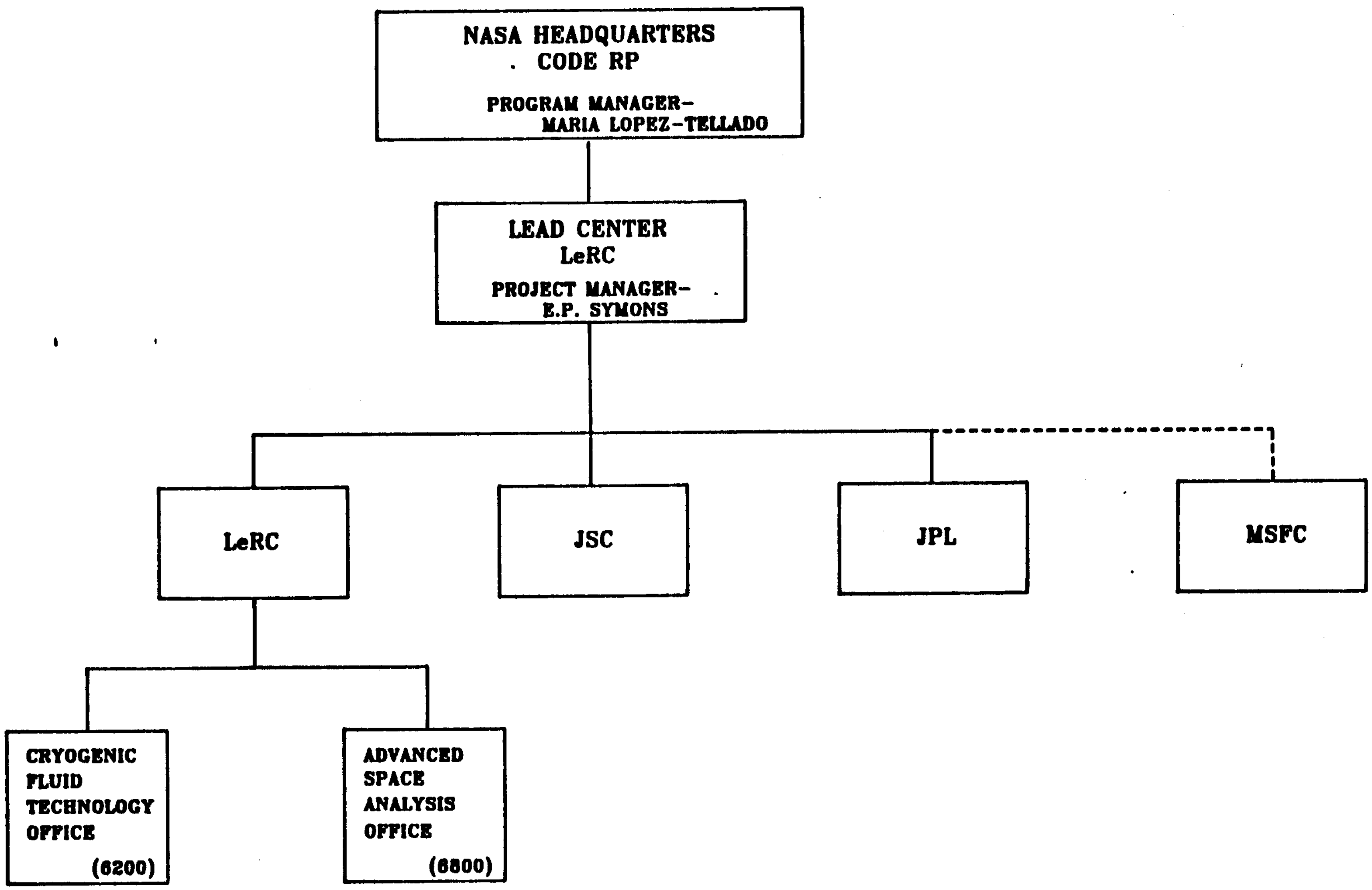
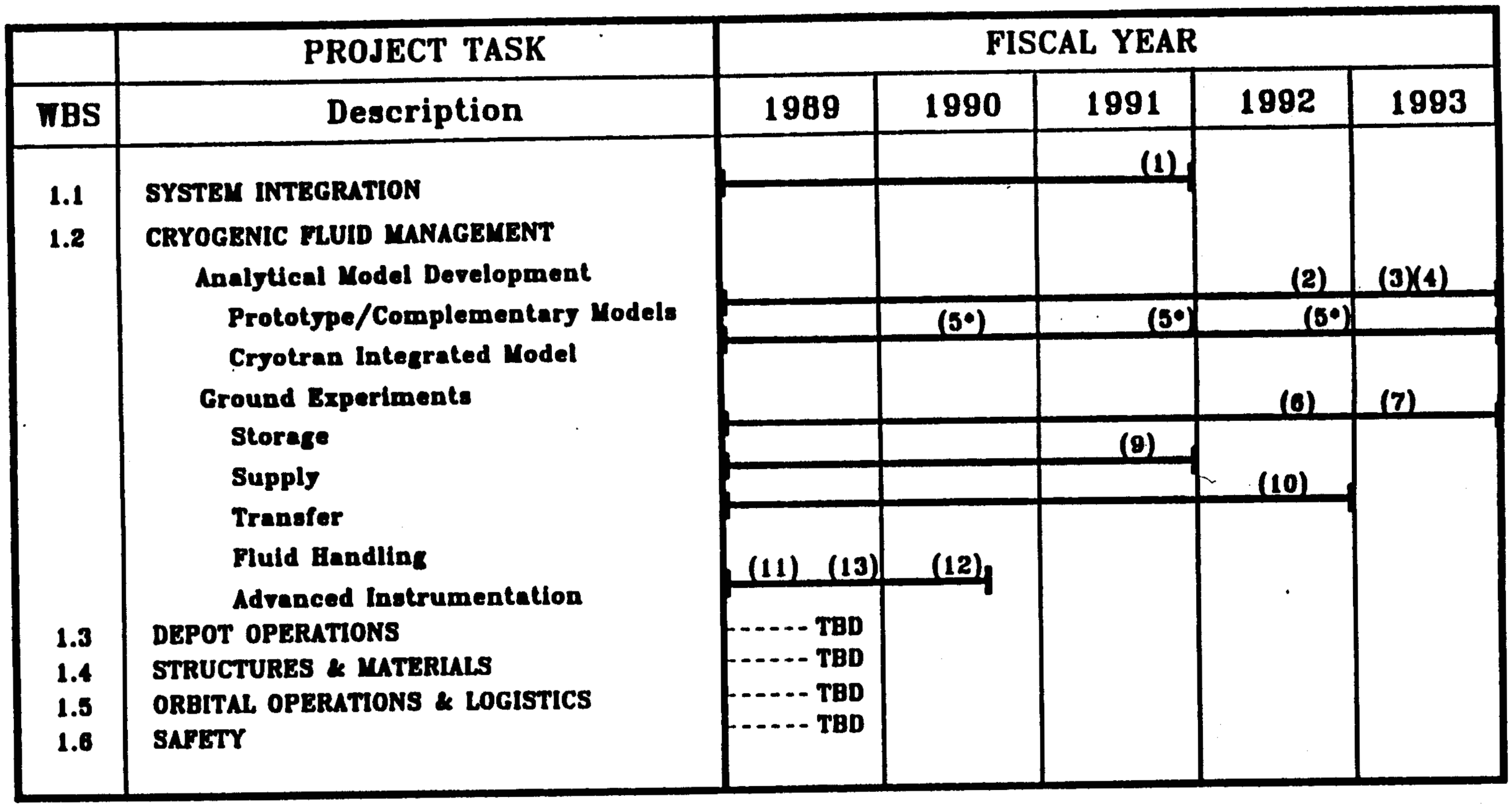


FIGURE 1–1 ORGANIZATION AND MANAGEMENT

dmw(1)(9-26-86)



*Indicates versions with partial 1-g validation

Figure 1-2 Five Year Schedule For The Cryogenic Fluid Depot

(5yr1-2)
dmw (9-1-88)

WBS	Milestone, Accomplishment or Deliverable	MILESTONE COMPLETE	TECHNOLOGY READINESS LEVEL		
			START	COMPLETE	REQ'D
1.1	**SYSTEM INTEGRATION**				
	(1) Detail Tech. Development Plan	*Sep. 1991*			
1.2	**CRYOGENIC FLUID MANAGEMENT**				
	Analytical Model Development				
	(2) 1-g Supply Validated	*Mar. 1992*	2	4	6
	(3) 1-g Pressure Control Validation	*Dec. 1992*	2	4	6
	(4) 1-g Fluid Transfer Validation	*Mar. 1993*	2	4	6
	(5) CRYOTRAN Release with 1-g Validation	*June 1993*	2	4	6
	Ground Experiments				
	(6) 1-g Pressure Control Data Base	*June 1992*	2	4	6
	(7) Depot Thermal Control T.A.	*Dec. 1992*	2	N/A	6
	(8) Storage Thermal Control Dev.	*Dec. 1995*	2	6	6
	(9) 1-g Supply Data Base Complete	*Oct. 1991*	2	4	6
	(10) 1-g Fluid Transfer Data Base	*Nov. 1992*	2	4	6
	(11) LH2 Flight Mass Flowmeter Dev.	*Mar. 1989*	2	3	5
	(12) 1-g Test of LH2 Flowmeter Comp.	*July 1990*	2	5	5
	(13) Quantity Gauging Device Dev.	*Sep. 1989*	2	5	5
1.3	**DEPOT OPERATIONS**	*TBD*			
1.4	**STRUCTURE & MATERIALS**	*TBD*			
1.5	**ORBITAL OPERATIONS & LOGISTICS**	*TBD*			
1.6	**SAFETY**	*TBD*			

Table 1–1 Milestones, Accomplishments, and Deliverables

(tbl11)
dmw(9-1-88)

Resources	Schedule (Fiscal Years)				
	1989	1990	1991	1992	1993
Funding ($,K)	3000	5000	8000	8000	8000
NASA Workforce (WY/Y)	22	23	24.5	25	29

Table 1-2 Resources Requirements for the Cryogenic Fluid Depot

(tbl1-2)
dmw(9-1-88)

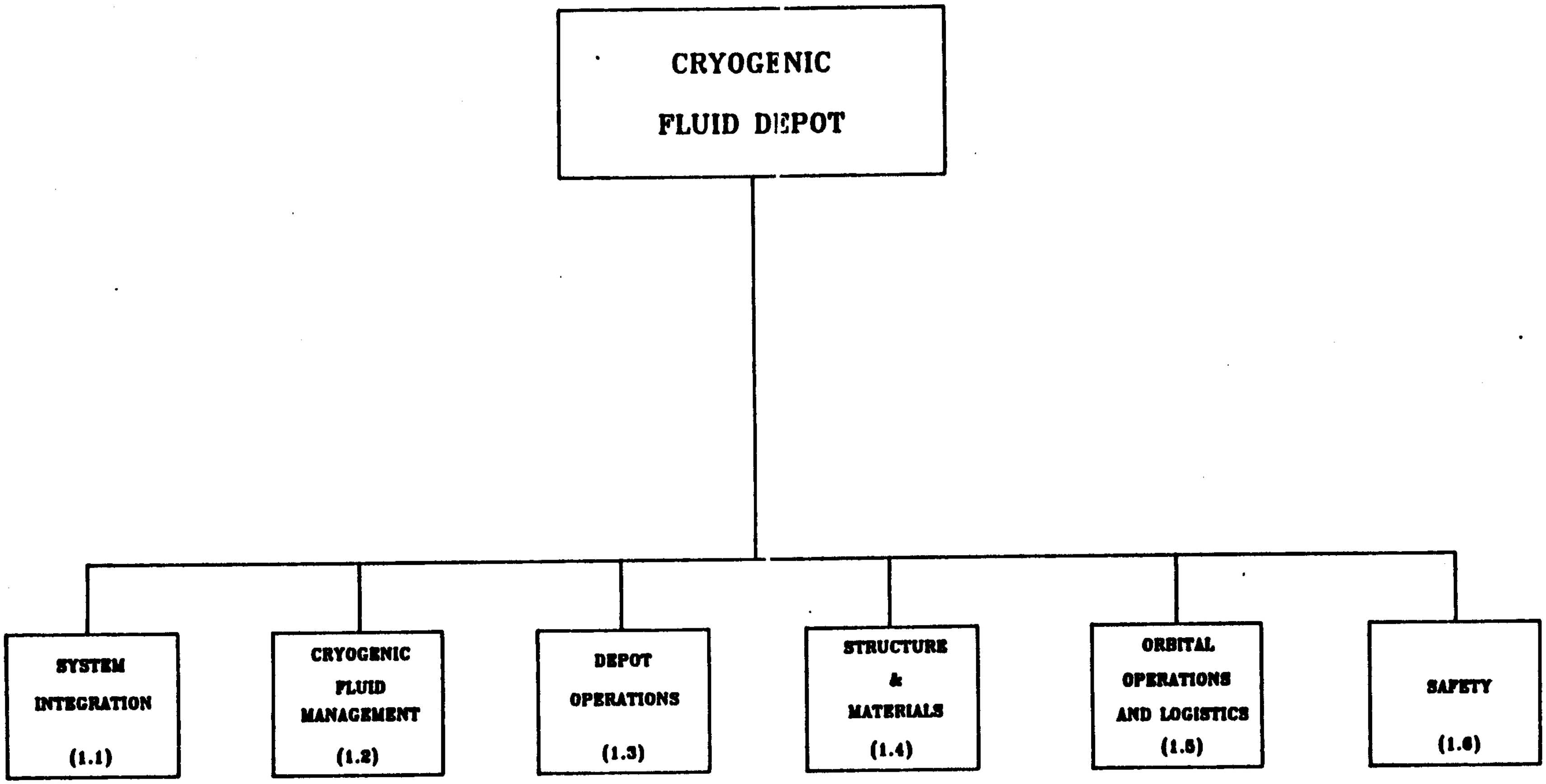


FIGURE 4-1 PROJECT WORK BREAKDOWN STRUCTURE

dmw(2)(9-28-88)

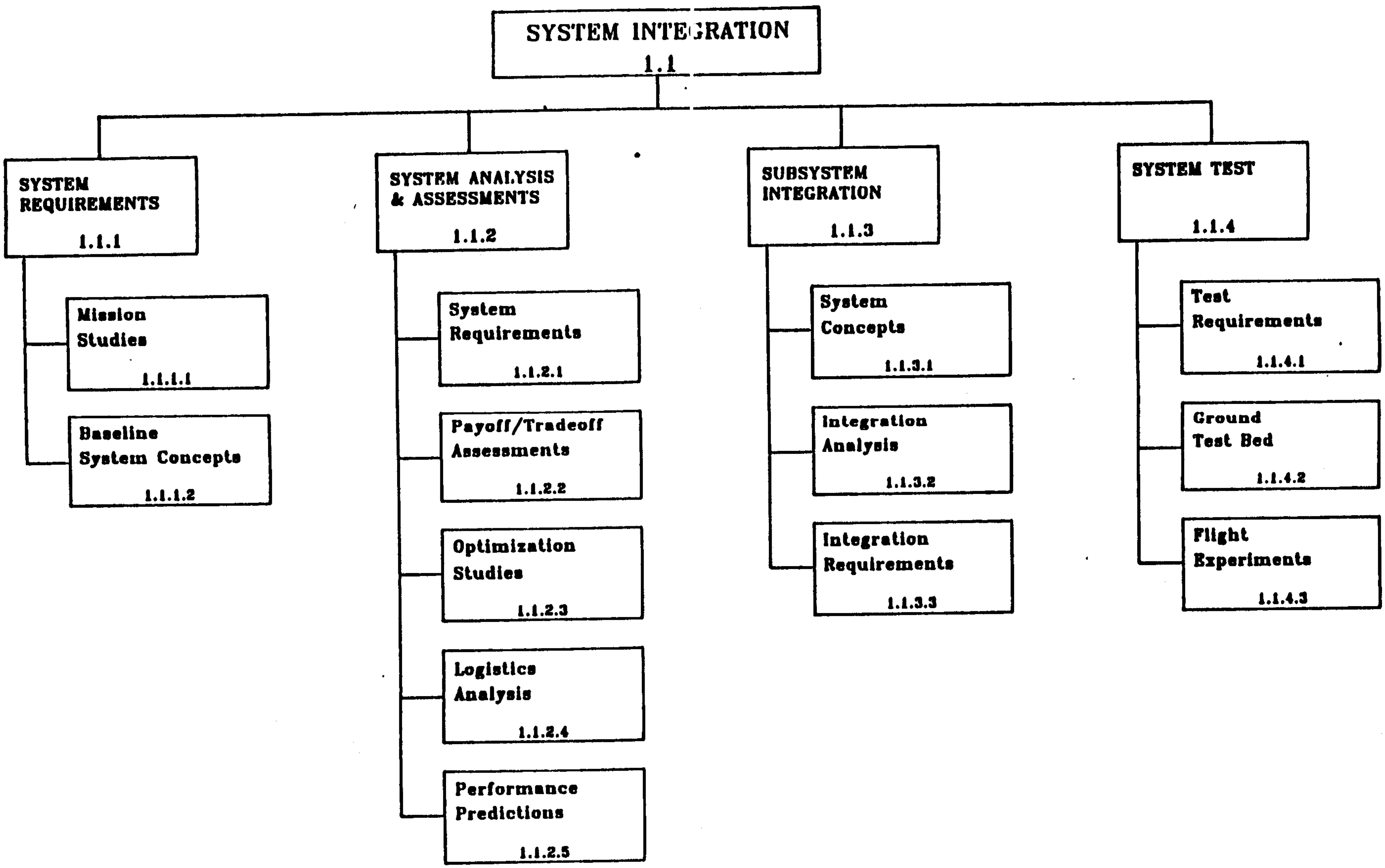


FIGURE 4–2 TASK 1.1 AND SUBTASK WORK BREAKDOWN STRUCTURE

(3)
dmw(9-28-88)

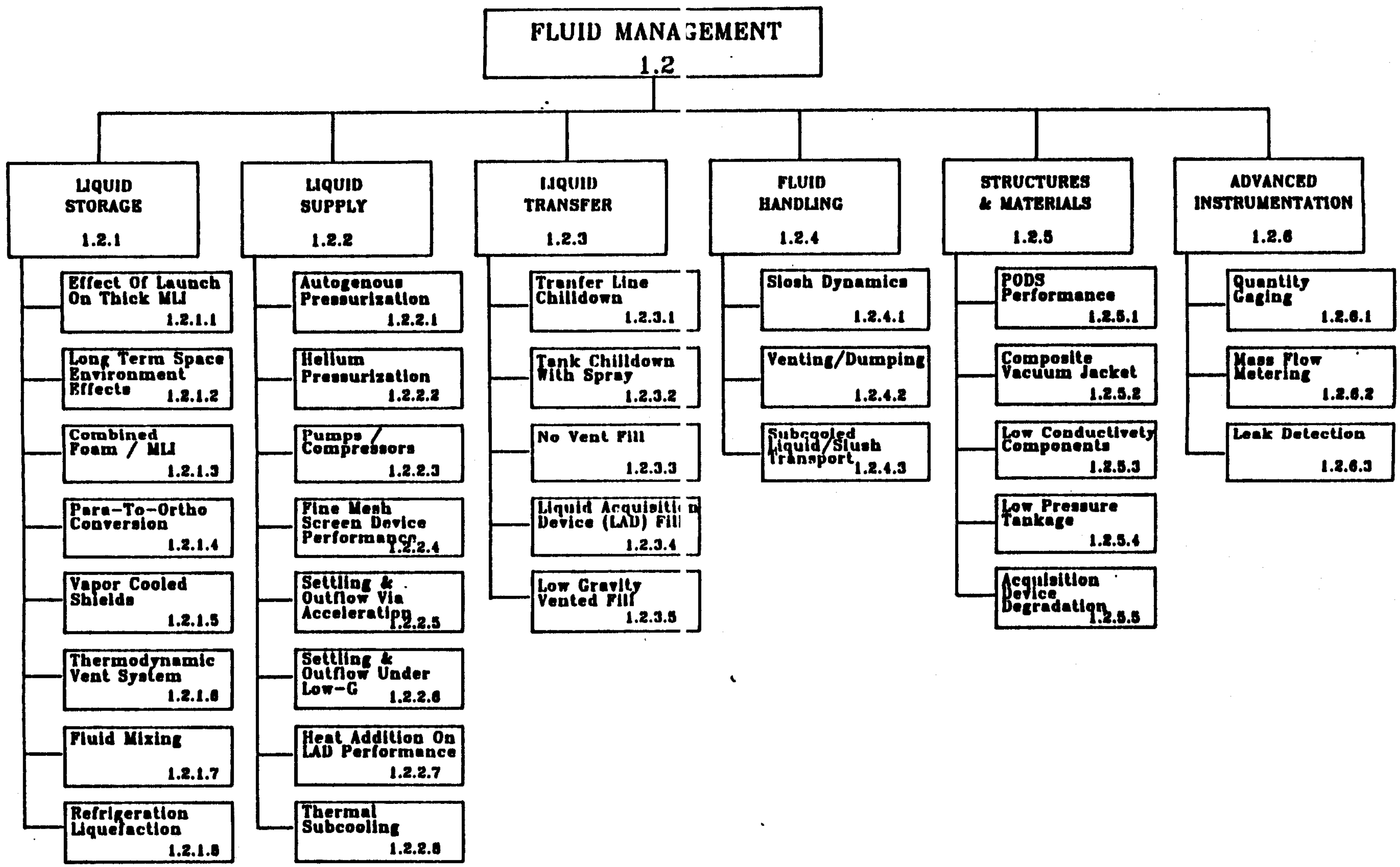


FIGURE 4-3 TASK 1.2 AND SUBTASK WORK BREAKDOWN STRUCTURE

(4)
dmw(9-28-88)

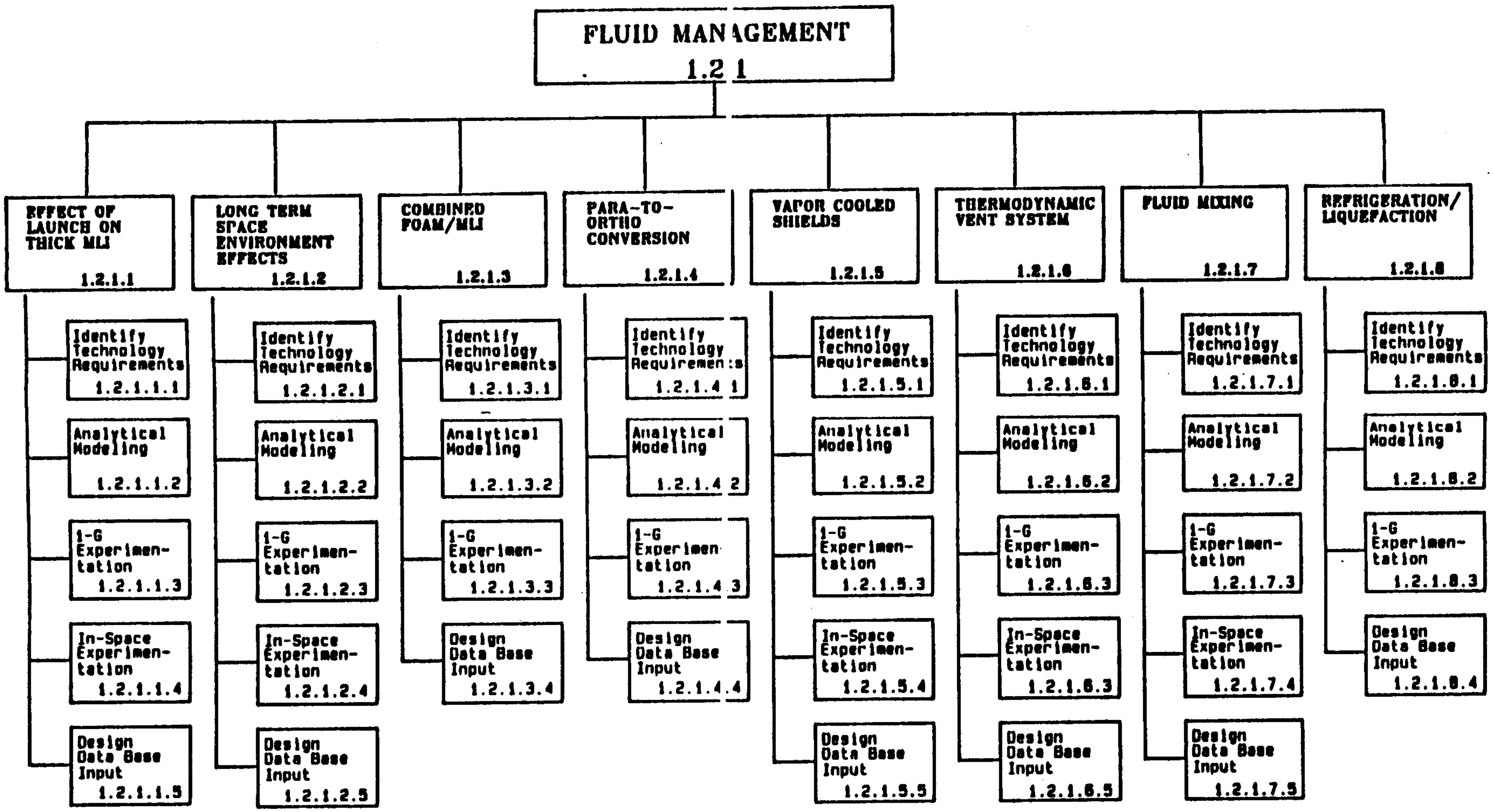


FIGURE 4-3a SUBTASK 1.2.1 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

dmw(9-28-88)(5)

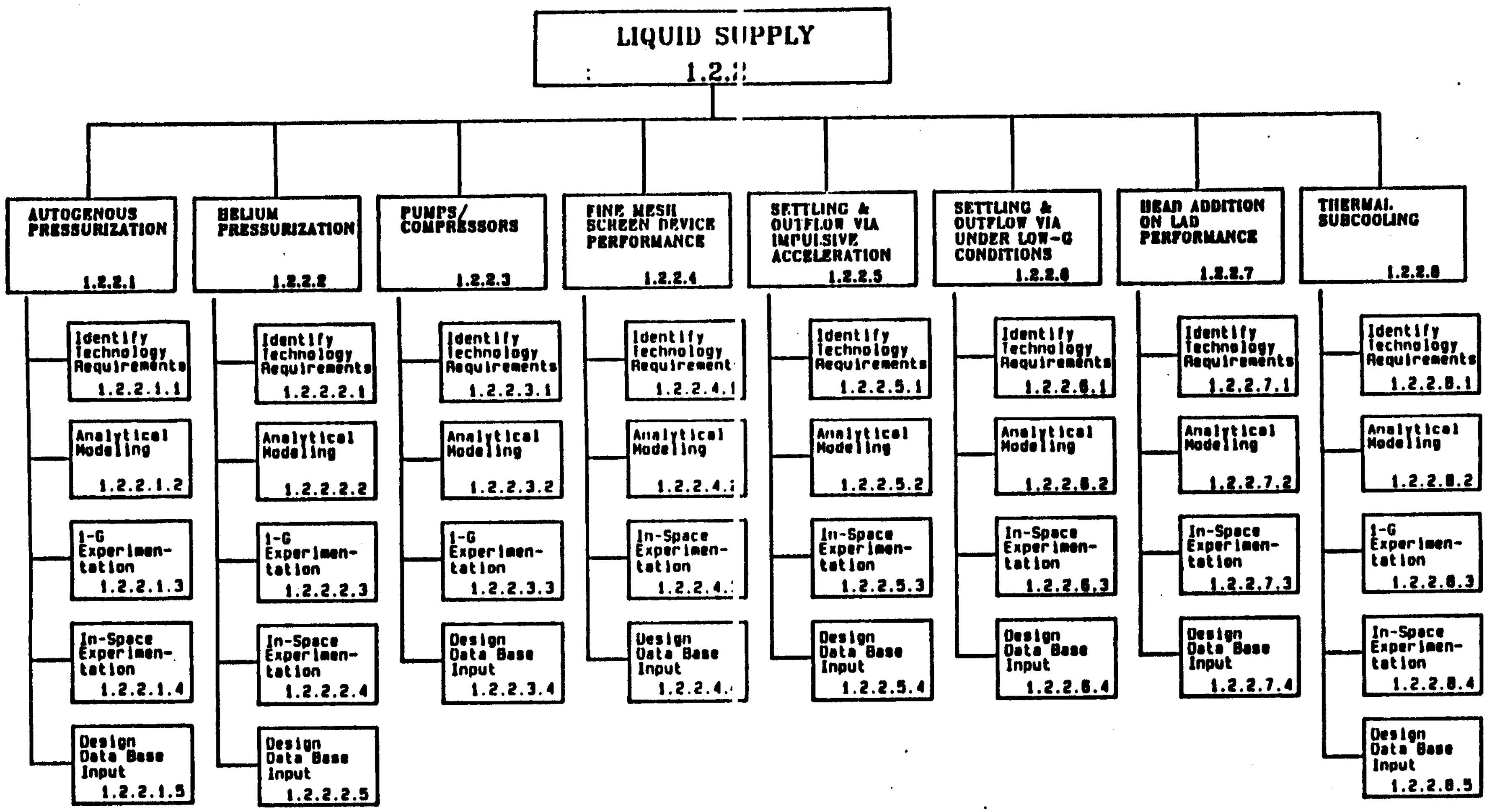


FIGURE 4-3b SUBTASK 1.2.2 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

dmw(9-1-88) (6)

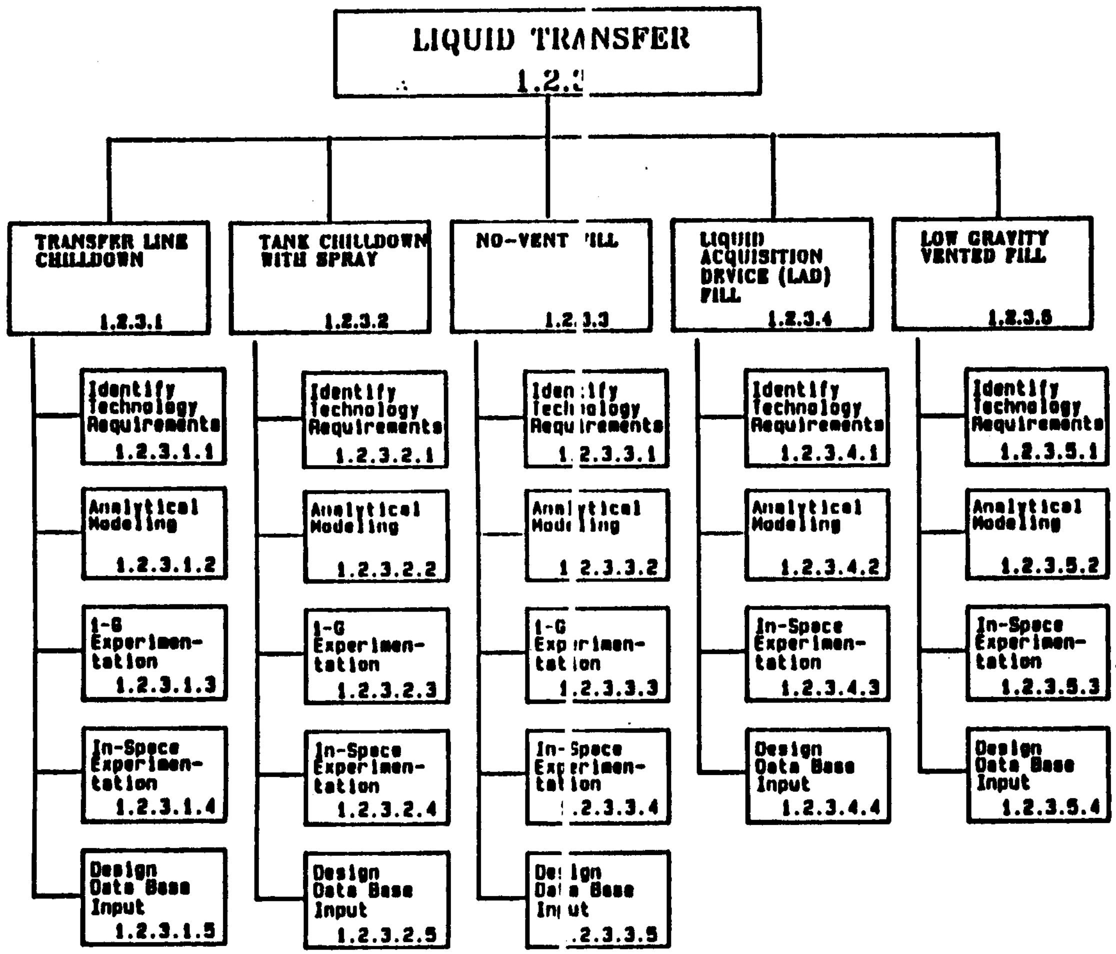


FIGURE 4–3c SUBTASK 1.2.3 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

dmw(9-1-88) (7)

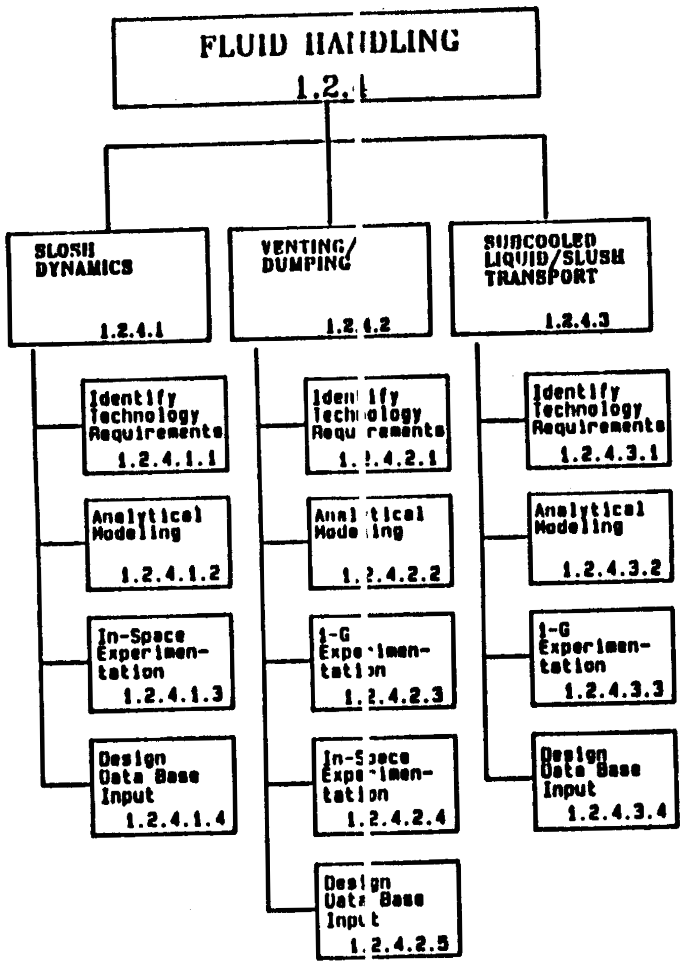


FIGURE 4–3d SUBTASK 1.2.4 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

dmw(8)(9-1-88)

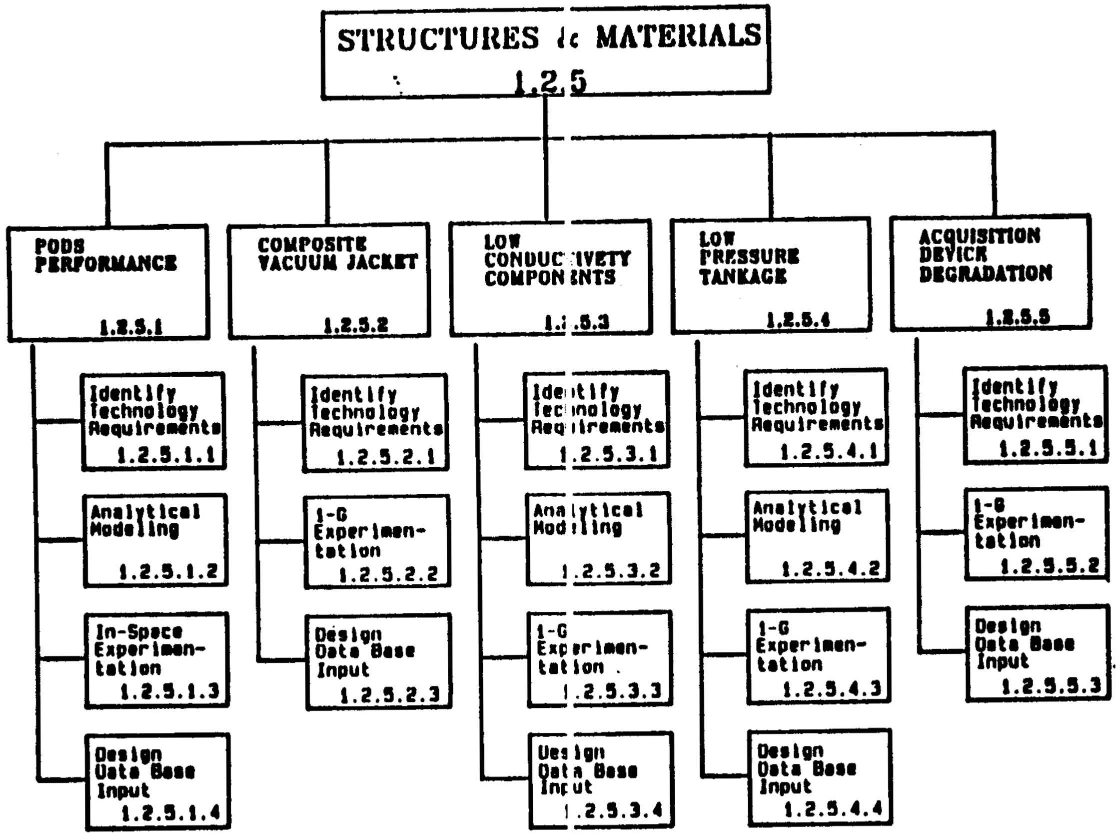


FIGURE 4-3e SUBTASK 1.2.5 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

dmw(9)(9-1-88)

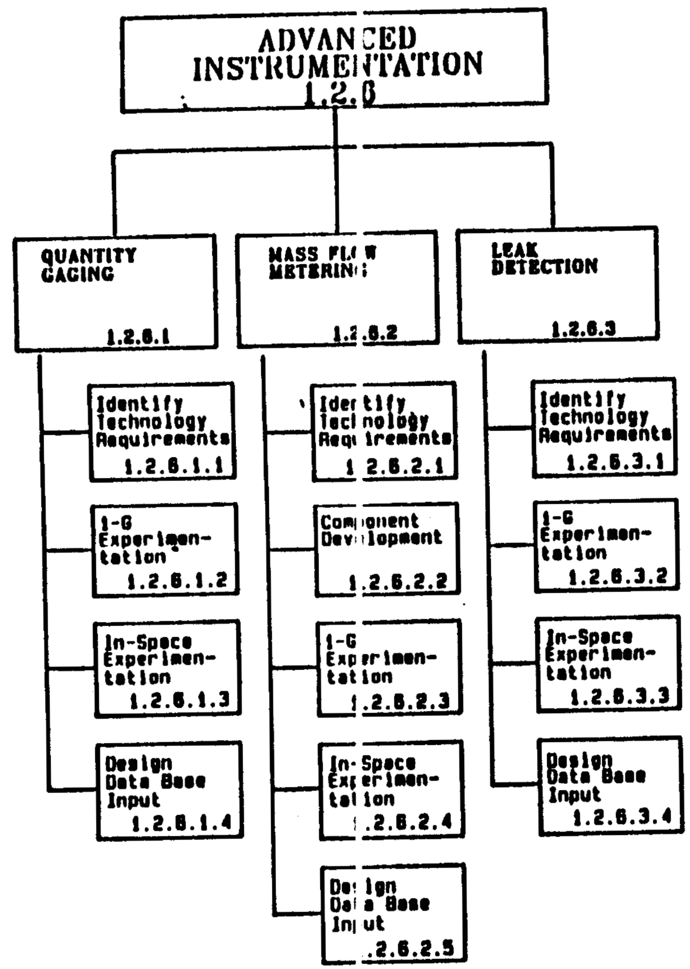
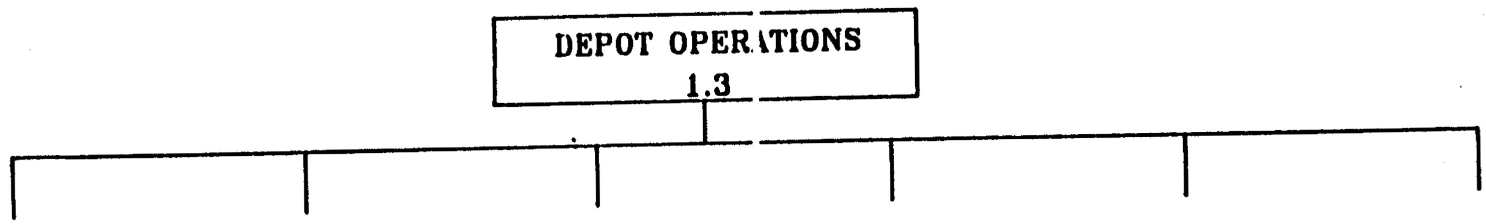


FIGURE 4-3f SUBTASK 1.2.6 & WORK PACKAGE WORK BREAKDOWN STRUCTURE

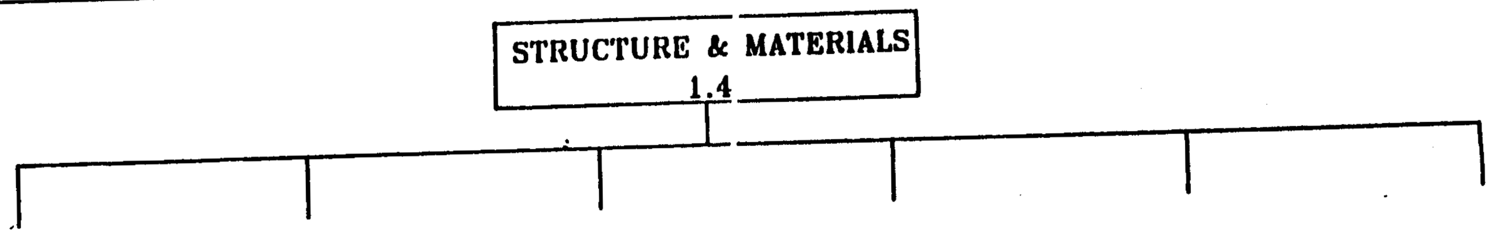
dmw (10) (9-1-88)



TO BE DETERMINED

FIGURE 4–4 TASK 1.3 AND SUBTASK WORK BREAKDOWN STRUCTURE

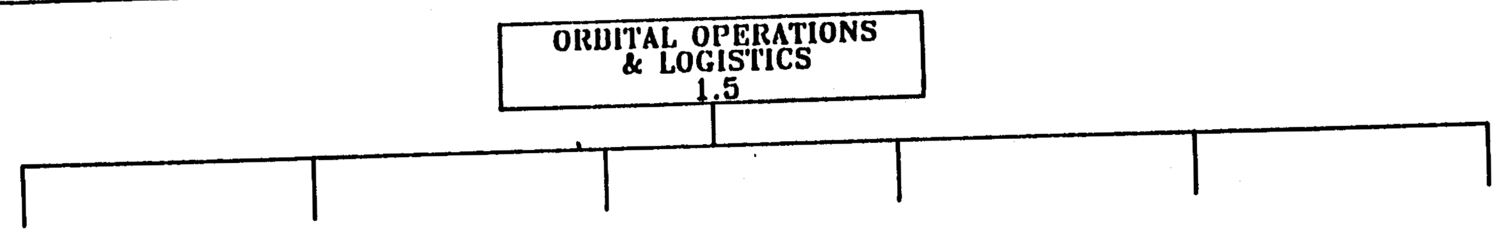
(1-3)
dmw(9-28-88)



TO BE DETERMINED

FIGURE 4–5 TASK 1.4 AND SUBTASK WORK BREAKDOWN STRUCTURE

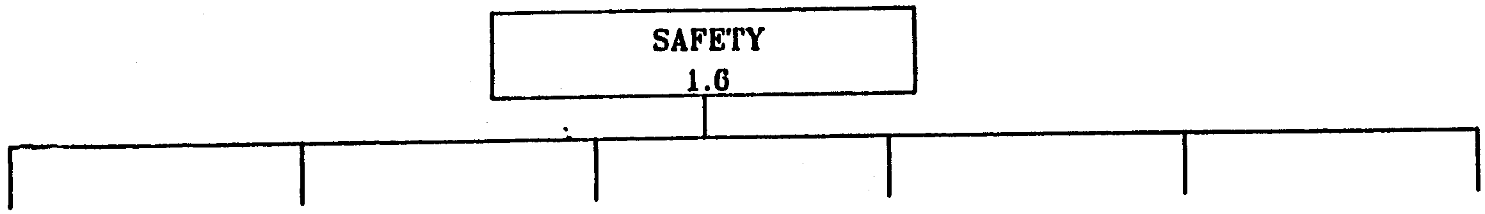
(1.4)
dmw(9-28-88)



TO BE DETERMINED

FIGURE 4–6 TASK 1.5 AND SUBTASK WORK BREAKDOWN STRUCTURE

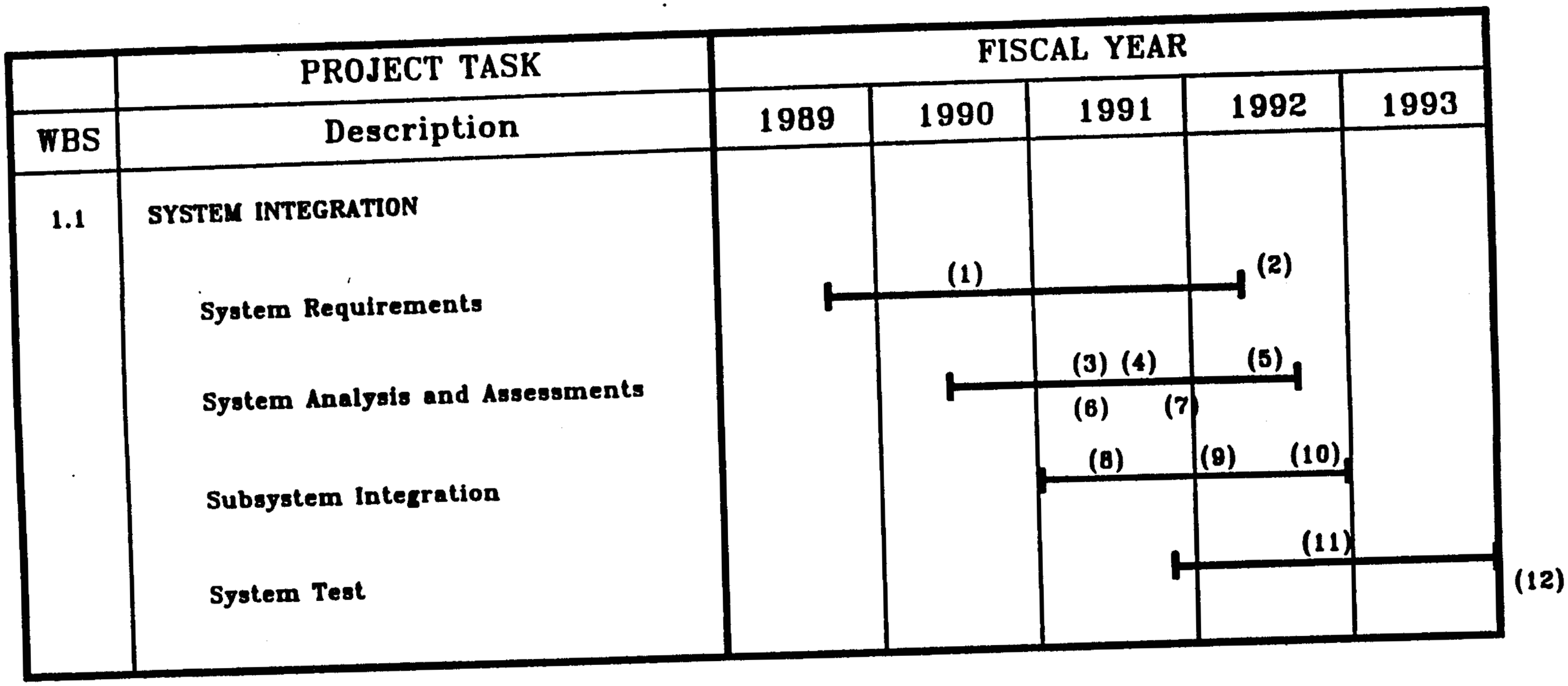
(1.5)
dmw(9–28–88)



TO BE DETERMINED

FIGURE 4–7 TASK 1.6 AND SUBTASK WORK BREAKDOWN STRUCTURE

(1.6)
dmw(9–28–88)



System Requirements	
(1) Mission Studies	Jun. 1990
(2) System Concepts	Nov. 1991
System Analysis And Assessments	
(3) System Requirements	Jan. 1991
(4) Tradeoff Studies	Apr. 1991
(5) Optimization	May 1992
(6) Logistics Analysis	Mar. 1991
(7) Performance Predictions	Aug. 1991
Subsystem Integration	
(8) System Concepts	Apr. 1991
(9) Integration Analysis	Sept. 1991
(10) Integration Requirements	July 1992
System Test	
(11) Test Requirements	Aug. 1992
(12) Ground Test Bed	Dec. 1995

Figure 5-1 Five Year Schedule Of Milestones And Deliverables For Systems Integration Task 1.1

(fig__) dmw (9-30-88)

PROJECT TASKS		FISCAL YEAR				
WBS	Description	1989	1990	1991	1992	1993
1.1	SYSTEM INTEGRATION					
	Definition Studies	0.17	0.50	0.60	0.20	
	Ground Testing (Test Bed)					
	K-Site - Research Hardware				2.6	2.3
	- Testing/SSC					.7
	Total $M	0.170	0.500	0.600	2.800	3.000

Table 5–1 Five Year Funding Resources For The System Integration Task 1.1

(fig5-1)
dmw(9-30-88)

PROJECT TASK		FISCAL YEAR				
WBS	Description	1989	1990	1991	1992	1993
1.2	CRYOGENIC FLUID MANAGEMENT					
	Analytical Model Development				(2)	(3)(4)
	Prototype/Complementary Models		(5*)	(5*)	(5*)	(5)
	Cryotran Integrated Model					
	Ground Experiments				(6)	(7) (8)
	Storage			(9)		
	Supply				(10)	
	Transfer					
	Fluid Handling	(11) (13)	(12)			
	Advanced Instrumentation					

*Indicates versions with partial 1-g validation
NOTE: ITEM (1) DELETED

Analytical Model Development	COMPLETED
(2) 1-g Supply Validated	Mar. 1992
(3) 1-g Pressure Control Validation	Dec. 1992
(4) 1-g Fluid Transfer Validation	Mar. 1993
(5) CRYOTRAN Release with 1-g Validation	June 1993

Ground Experiments	COMPLETED
(6) 1-g Pressure Control Data Base	June 1992
(7) Depot Thermal Control T.A.	Dec. 1992
(8) Storage Thermal Control Dev.	Dec. 1995
(9) 1-g Supply Data Base Complete	Oct. 1991
(10) 1-g Fluid Transfer Data Base	Nov. 1992
(11) LH2 Flight Mass Flowmeter Dev.	Mar. 1989
(12) 1-g Test of LH2 Flowmeter Comp.	July 1990
(13) Quantity Gauging Device Dev.	Sep. 1989

Figure 5-2 Five Year Schedule Of Milestones And Deliverables For Cryogenic Fluid Management Task 1.2

(5yr)
dmw (9-1-88)

Analytical Model	Thermodynamic Childown	No Vent Fill Bulk Liquid Transport	No Vent Fill Interface Kinetics	Transient Childown
Description	• Thermodynamic lumped parameter model "Quasi Equilibrium" • Uses energy equation to determine thermodynamic state • Calculates required wall cooling • Determines max mass which will not over-pressure tank • Calculates mass injection	• Thermodynamic lumped parameter • Uses convective heat transfer equation • Predicts mass transfer at interface • Calculates initial pressure rise due to flashing and residual wall energy • Predicts pressure rise in No Vent Fills	• Thermodynamic lumped parameter • Uses kinetic theory to predict mass transfer at liquid/vapor interface • Predicts pressure rise in No Vent Fill	• Thermodynamic lumped parameter • Extends thermodynamic childown to transient domain • Uses convective heat transfer to determine wall temperature • Adds heat leak at wall
Use	• Prediction of target temperature • Prediction of childown mass	• Prediction of transients in No Vent Fills dominated by convection	• Prediction of transients in No Vent Fills dominated by gas kinetics	• Prediction of transient effects on the childown process

TABLE 5-2 IN - HOUSE PROTOTYPE MODELS

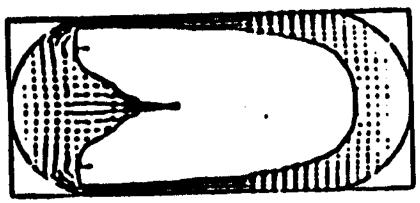
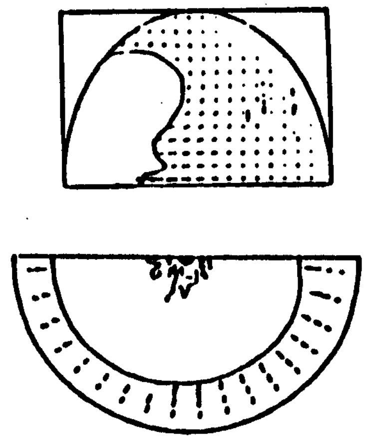
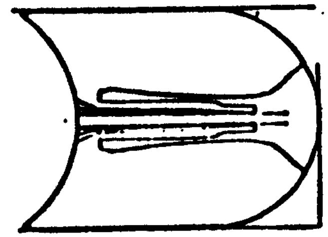
Analytical Model	NASA - VOF2D Los Alamos National Lab (LANL)	NASA - VOF3D (LANL)	SOLA - ECLIPSE (Washington University at St. Louis)
Description and Sample Output	 • 2-D, transient, Free surface hydrodynamics • Fractional Volume of fluid method • Multiple free surfaces • Surface tension, wall adhesion • Curved boundries, interior obstacles • Variable low-g levels	 • 3-D, transient, free surface hydrodynamic • Cylindrical geometry • Extends NASA-VOF2D to 3 dimensions	 • Superimposes energy equation on VOF2D • Adds turbulent K-E model • Adds inflow • Tracks ullage thermodynamics
Use	• Reorientation, draining, settling	• Slosh, off axis settling	• Pressure control, fluid mixing

TABLE 5-3 COMPLEMENTARY MODELS
(CONTRACTED: LeRC MANAGER)

DMW (2-5-88) a.models.dc

SPACE FLIGHT SYSTEMS DIRECTORATE

CRYOGENIC FLUIDS TECHNOLOGY OFFICE

NASA Lewis Research Center

Work Package Breakdown

Grouping of CryoTran problem set by commonality of key processes and solution techniques

A) Preprocessor

B) Postprocessor

C) Heat Exchange
- Wall mounted H-X
- L.A.D. H-X
- Chill via Cyclic Vent
- Transfer Line Chill

D) Insulation
- Vapor Cooled Shield
- Heat Leak along Strut
- Heat Leak along Penetration

E) Thermodynamic
- No Vent Fill via Axial Spray
- Chill via Drop Spray
- Autogenous Pressurization

F) VOF2D interface
- H-X and Mixer
- Propellant Settling

G) L.A.D.
- Fill of Total L.A.D.
- Fill of Partial L.A.D
- L.A.D. flow

H) Fluid Dynamic
- Slosh in Bare Tank
- Slosh with Ring Baffle

I) 3-D Spray
- Chill via Tangential Spray
- NVF via Tangential Spray
- NVF via Radial Spray

TABLE 5-4

NASA
Lewis Research Center

APPROVAL: E. P. Symons

NARRATIVE ANALYSIS

Cryogenic Fluid Management Technology Program

CFTO Cryogenic Fluids Technology Office

STATUS AS OF June 30, 1988

TECHNOLOGY READINESS LEVELS

LEVEL 1 -- Basic principles observed and reported

LEVEL 2 -- Conceptual design formulated

LEVEL 3 -- Conceptual design tested analytically or experimentally

LEVEL 4 -- Critical function breadboard demonstrated

LEVEL 5 -- Component tested in relevant environment

LEVEL 6 -- Subscale system model tested in relevant environment

LEVEL 7 -- Prototype system tested in space

LEVEL 8 -- Baselined into production design

TECHNOLOGY CRITICALITY LEVELS

LEVEL 1 -- Enabling - Specific application cannot be configured without this technology

LEVEL 2 -- Enhancing - Technology provides system performance improvement or reduced operational complexity/cost

TABLE 5-5

PROJECT TASKS		FISCAL YEAR				
WBS	Description	1989	1990	1991	1992	1993
1.2	CRYOGENIC FLUID MANAGEMENT					
	Co-Investigators	0.28	0.4	0.5	0.5	0.5
	Analytical Modeling					
	Grants – MIT	0.085	0.1	0.1	0.1	0.1
	– Washington U.	0.08	0.1	0.1	0.1	0.1
	– Los Alamos NL	0.15	0.2	0.3	0.4	0.4
	Ground Testing					
	K-Site – Research Hardware	0.282	0.5	0.5		
	– Testing/SSC	0.47	0.6	0.7	0.7	0.7
	FML-4 – Research Hardware		0.05	0.05	0.05	
	– Testing/SSC		0.05	0.05	0.05	
	FML-7 – Research Hardware	0.1	0.1	0.2	0.2	0.2
	– Testing/SSC	0.08	0.1	0.1	0.1	0.1
	CRL-13 – Research Hardware	0.05	0.1	0.1	0.1	0.1
	– Testing/SSC	0.08	0.1	0.1	0.05	0.05
	Component Development					
	– Mixers		0.2	1.3	0.22	
	– Pumps		0.2	1.3	0.22	
	– Refrigerators					0.3
	Project Management	0.12	0.15	0.2	0.21	0.22
	Analex/Sverdrup/ED Support	0.729	1.25	1.3	1.35	1.4
	Program Support	0.256	0.3	0.5	0.6	0.6
	Management Reserve				0.25	0.23
	Total $M	2.762	4.500	7.400	5.200	5.000

Table 5–6 Five Year Funding Resources For The Cryogenic Fluid Management Task 1.2

(fig8)
dmw(8-7-88)

CRYOGENIC FLUID MANAGEMENT TECHNOLOGY PROGRAM

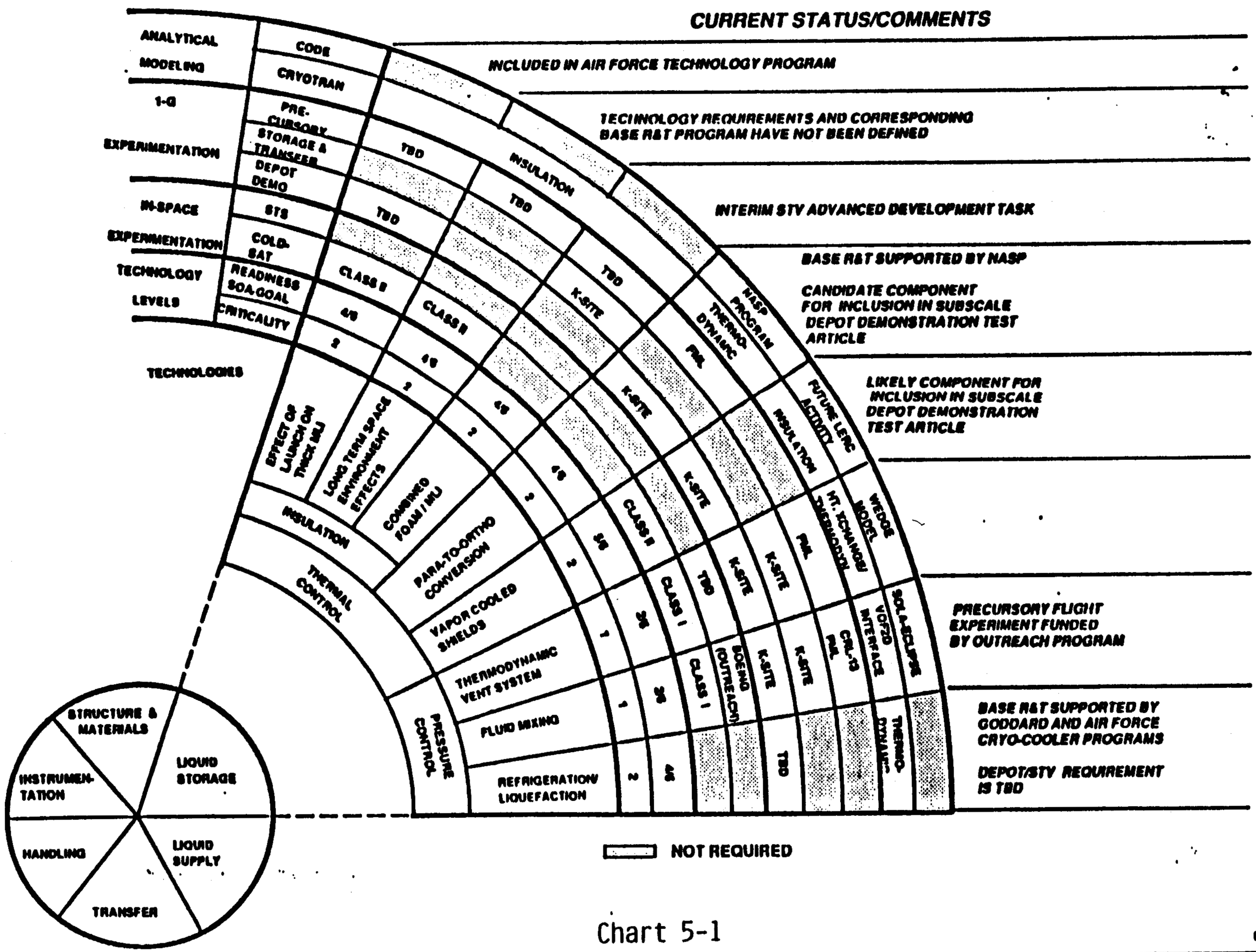


Chart 5-1

CRYOGENIC FLUID MANAGEMENT TECHNOLOGY PROGRAM

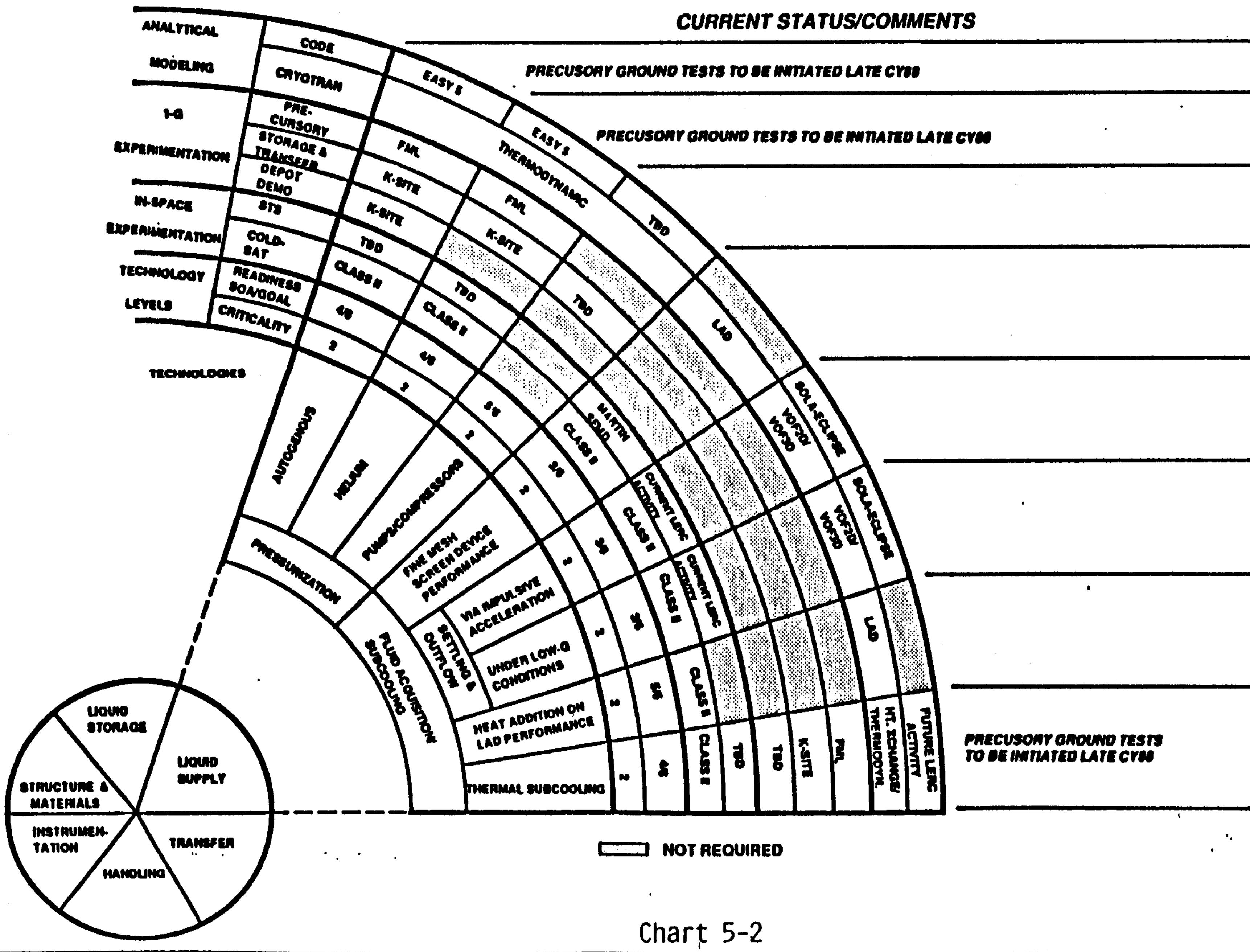
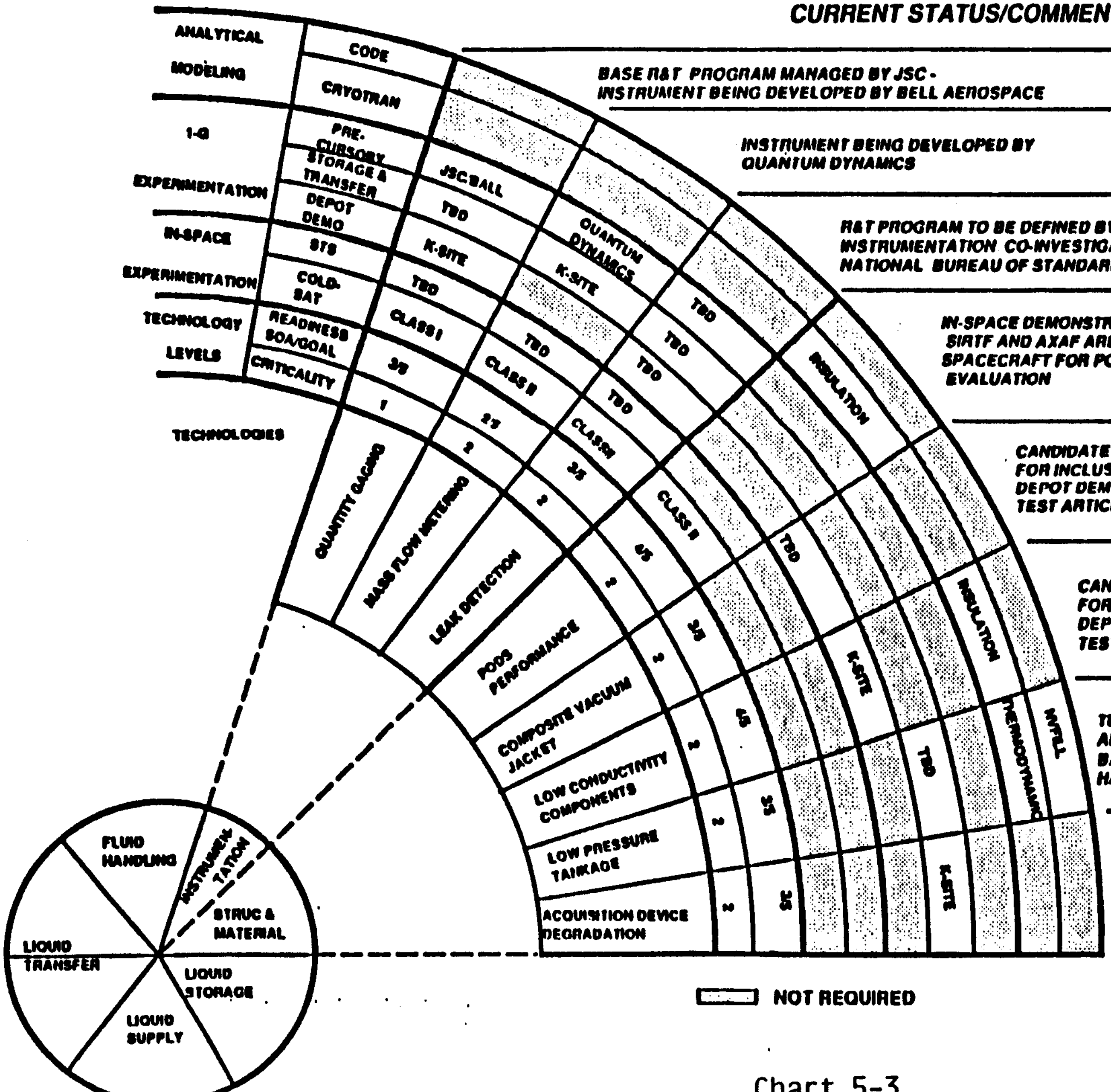


Chart 5-2

CRYOGENIC FLUID MANAGEMENT TECHNOLOGY PROGRAM



CURRENT STATUS/COMMENTS

BASE R&T PROGRAM MANAGED BY JSC - INSTRUMENT BEING DEVELOPED BY BELL AEROSPACE

INSTRUMENT BEING DEVELOPED BY QUANTUM DYNAMICS

R&T PROGRAM TO BE DEFINED BY ADVANCED INSTRUMENTATION CO-INVESTIGATOR FROM NATIONAL BUREAU OF STANDARDS

IN-SPACE DEMONSTRATION DESIRED-SIRTF AND AXAF ARE ALSO CANDIDATE SPACECRAFT FOR PODS PERFORMANCE EVALUATION

CANDIDATE COMPONENT FOR INCLUSION IN SUBSCALE DEPOT DEMONSTRATION TEST ARTICLE

CANDIDATE COMPONENT FOR INCLUSION IN SUBSCALE DEPOT DEMONSTRATION TEST ARTICLE

TECHNOLOGY REQUIREMENTS AND CORRESPONDING BASE R&T PROGRAM HAVE NOT BEEN DEFINED

TECHNOLOGY REQUIREMENTS AND CORRESPONDING BASE R&T PROGRAM HAVE NOT BEEN DEFINED

Chart 5-3

BKT 07/19/88

CRYOGENIC FLUID MANAGEMENT TECHNOLOGY PROGRAM

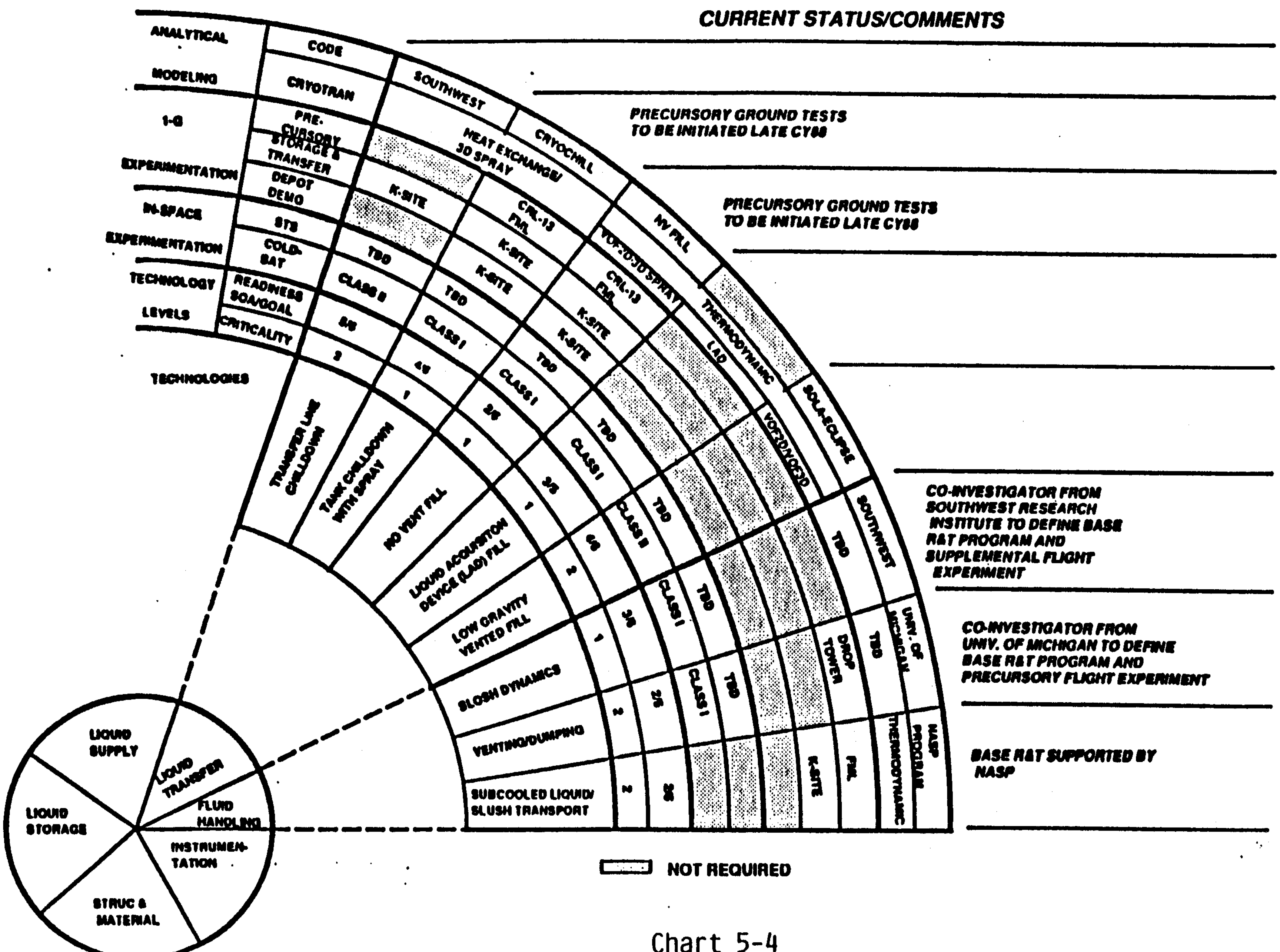


Chart 5-4

BKT 07/19/88

PROJECT TASKS		COSTS	
WBS	Description	Subtask	Task
1.1	SYSTEM INTEGRATION		*0.17*
	Mission Studies	*0.17*	
1.2	CRYOGENIC FLUID MANAGEMENT		*2.762*
	Co-Investigators	*0.28*	
	Analytical Modeling		
	Grants – MIT	*0.085*	
	– Washington U.	*0.08*	
	– Los Alamos NL	*0.15*	
	Ground Testing		
	K-Site – Research Hardware	*0.282*	
	– Testing/SSC	*0.47*	
	FML-7 – Research Hardware	*0.1*	
	– Testing/SSC	*0.08*	
	CRL-13 – Research Hardware	*0.05*	
	– Testing/SSC	*0.08*	
	Project Management	*0.12*	
	Analex/Sverdrup/ED Support	*0.729*	
	Program Support	*0.256*	
1.3	DEPOT OPERATIONS		*0*
1.4	STRUCTURES & MATERIALS		*0*
1.5	ORBITAL OPERATIONS & LOGISTICS		*0*
1.6	SAFETY		*0*
	Total		*2.932*

Table 6–1 Fiscal Year 1989 Funding Requirements For The Cryogenic Fluid Depot

(tbl81)
dmw(8-7-88)

PROJECT TASKS		FISCAL YEAR				
WBS	Description	1989	1990	1991	1992	1993
1.1	SYSTEM INTEGRATION	0.17	0.5	0.6	2.8	3.0
1.2	CRYOGENIC FLUID MANAGEMENT	2.762	4.5	7.4	5.2	5.0
1.3	DEPOT OPERATIONS	0	0	0	0	0
1.4	STRUCTURES & MATERIALS	0	0	0	0	0
1.5	ORBITAL OPERATIONS & LOGISTICS	0	0	0	0	0
1.6	SAFETY	0	0	0	0	0
	Total $M	2.932	5.000	8.000	8.000	8.000

Table 6–2 Five Year Funding Requirements For The Cryogenic Fluid Depot

(tbl6-2)
dmw(9-7-88)

PROJECT TASKS		
WBS	Description	Workforce
1.1	SYSTEM INTEGRATION	
	Study–Professional	1.0
	Procurement	0.5
1.2	CRYOGENIC FLUID MANAGEMENT	
	Management	2.0
	Principal Investigator	0.5
	Procurement	1.5
	Analytical Modeling–Professional	4.0
	Ground Testing – Professional	8.5
	– Technical Support	4.0
1.3	DEPOT OPERATIONS	0
1.4	STRUCTURES & MATERIALS	0
1.5	ORBITAL OPERATIONS & LOGISTICS	0
1.6	SAFETY	0
	Total Workforce	22.0

Table 6–3 Fiscal Year 1989 Workforce Requirements For The Cryogenic Fluid Depot

(tbl6–3)
dmw(9–7–88)

PROJECT TASKS		FISCAL YEAR				
WBS	Description	1989	1990	1991	1992	1993
1.1	SYSTEM INTEGRATION	1.5	1.5	1.5	2.0	5.0
1.2	CRYOGENIC FLUID MANAGEMENT	20.5	21.5	23.0	23.0	22.0
1.3	DEPOT OPERATIONS	0	0	0	0	0.5
1.4	STRUCTURES & MATERIALS	0	0	0	0	0.5
1.5	ORBITAL OPERATIONS & LOGISTICS	0	0	0	0	0.5
1.6	SAFETY	0	0	0	0	0.5
	Total Workforce	22.0	23.0	24.5	25.0	29.0

Table 6–4 Five Year NASA Workforce Requirements
The Cryogenic Fluid Depot

(tbl6-4)
dmw(9-7-88)

REFERENCES

1. Proceedings of "Cryogenic Fluid Management Technology Workshop," Volumes I and II, Lewis Research Center, April 1987.

2. R. Stubbs, R. Corban, A. Willoughby, "On-Orbit Fuels Depot Technology Roadmap," report prepared by NASA Lewis Research Center for the NASA Office of Aeronautics and Space Technology, January 1988.

APPENDIX A WILL BE SUPPLIED LATER

APPENDIX B WILL BE SUPPLIED LATER

APPENDIX C

1. Cryogenic Technology Advisory Group, August 1988.

CHARTER

CRYOGENIC TECHNOLOGY ADVISORY GROUP

AUGUST 1988

NASA

OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY

CHARTER FOR
CRYOGENIC TECHNOLOGY ADVISORY GROUP

1.0 OBJECTIVE

This document constitutes the charter for the Cryogenic Technology Advisory Group.

2.0 AUTHORITY

The Cryogenic Technology Advisory Group is formed at the direction of the Associate Administrator for the Office of Aeronautics and Space Technology (OAST).

3.0 FUNCTIONS

3.0.1 The group's primary function is to assure that cryogenic fluid management program efforts supported by OAST and under the direction of the NASA Lewis Research Center (LeRC) continue to address technology issues pertinent to future NASA missions. An additional function of the group will be to attend the major reviews of LeRC contractual efforts and provide technical critique and comments to the Cryogenic Fluids Technology Office Manager and the Cryogenic Fluid Management Technology Coordination Committee (CFMTCC) in a timely manner. In this function, the group's technical critique will focus on the evaluation of Contractor analytical and experimental techniques to assure that technical objectives are not compromised.

3.0.2 As required, the group will make a report to the CFMTCC to advise the committee of the group's recommendations for the continuation or transfer of programmatic emphases including the development of flight experiments, ground-based test programs, and the development of analytical and computational models. The group will also advise the CFMTCC as to recent developments in cryogenic fluid management technology areas and assess their potential impact to the program elements.

3.0.3 As required, the Chairperson will brief the Associate Administrator for OAST, or his representatives, on recent developments in cryogenic fluid management technologies and the success of the various program elements in the development of the technologies.

4.0 MEMBERSHIP

4.0.1 Membership of the group will be composed of full-time employees of the Federal Government representing several NASA field centers and other Government agencies active in the development of cryogenic fluid management technologies. The members of the group shall be appointed by the Directors of the Propulsion, Power and Energy Division and the Flight Projects Division of the OAST. When concurred by both Directors, the a standing membership of the group can be changed by a majority vote of its members. The current membership of the group is set forth in Attachment A.

4.0.2 An ad hoc, nonvoting membership, consisting of Government and non-Government parties representing areas of technical expertise within cryogenic fluid management, shall be established to provide direct input to the group. A standing ad hoc membership shall be established and changed by the vote of the Group members. The current ad hoc membership of the Group is set forth in Attachment B.

5.0 MEETINGS

5.0.1 Meetings of the Group will be held at the call of the Chairperson and will not be held less than semiannually. The meetings are likely to be held in conjunction with a major contract review or a major technical conference. A quorum of the Group will be at least half of the members plus one. If circumstances arise where a quorum from the standing membership cannot be present and the Group must be convened, the Chairperson has the authority to draw upon the list of ad hoc members in Attachment B and select a full-time employee of the Federal Government to participate as a member of the Group on a temporary basis.

5.0.2 All meetings of the Group will be open to the ad hoc membership; however, the attendance of the ad hoc membership will only be required on an "as needed" basis as determined by the CTAG Chairperson and Executive Secretary.

5.0.3 The Executive Secretary of the Group is responsible for scheduling meetings, assisting the Chairperson with establishing agendas, ensuring that a quorum will be present, and arranging for appropriate technical minutes to be recorded.

5.0.4 The minutes of each meeting will be kept which will contain as a minimum:

a. the attendance list.

b. the agenda

c. a summary of matters discussed and conclusions reached.

d. minority views when recommendations reached are not unanimous.

e. a list of all action items assigned and due dates.

f. copies of all documents received, issued, or approved by the Group.

5.0.5 The accuracy of all minutes will be verified by concurrence of the Chairperson.

6.0 COMMITTEE RECORDS

All records and files of the group, including agendas, meeting minutes, studies, analyses, reports, working papers, and other documents made available to or prepared by or for the committee will be retained by the Executive Secretary of the Cryogenic Technology Advisory Group.

Attachment A

Cryogenic Technology Advisory Group Membership

Chairman:

John C. Aydelott
NASA Lewis Research Center

Executive Secretary:

David M. DeFelice
NASA Lewis Research Center

Members:	Organization
John M. Cramer	NASA George Marshall Space Flight Center
John W. Griffin	NASA Lyndon B. Johnson Space Center
Dr. Peter Kittel	NASA Ames Research Center
Richard H. Knoll	NASA Lewis Research Center
Dr. James Siegwarth	National Bureau of Standards
Roy A. Silver	Air Force Astronautics Lab